SUBNATIONAL CLIMATE FUND

Comparative Assessment of Recycling Technologies and Methods for Low-Value

Feasibility Study

Plastic Waste

Acknowledgements

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Executive Summary

This comparative study on plastic recycling technologies reveals that **<u>the primary challenge in managing plastic waste is not the recycling process itself, but rather the collection stage</u>**. Only waste that is properly collected can be recycled, and in regions lacking formal waste management systems, recycling efforts are typically limited to rigid plastic waste with a high mass-to-volume ratio. Informal waste collectors tend to prioritize such plastics due to the higher revenues they generate, often neglecting lower-value plastics like flexible packaging.

Figure 1: Example of low value plastics

The study distinguishes between tw **<u>open-loop (or down-cycling)</u>**. Closed-loop recycling aims to keep plastics within the plastic material cycle, allowing for multiple reuse cycles and high-quality recyclates. Open-loop recycling, on the other hand, focuses on converting plastics into materials that substitute for other substances, such as gravel or wood, and often involves lower-quality recyclates and consequentially result in losing the material plastic in the plastics value chain.

Direct comparisons between closed-loop and open-loop recycling technologies are difficult. Closed-loop recycling is aimed at returning plastic to the plastics value chain, whereas open-loop recycling provides temporary solutions by creating products from plastic waste that may not re-enter the plastic cycle at their end of life. This makes **<u>open-loop technologies</u>** more suitable **<u>as "bridging technologies"</u>**, particularly in regions with limited waste management infrastructure, as they demand lower input quality.

Regardless of the technology employed, **<u>pre-conditioning of plastic waste is essential</u>** to meet process requirements and deliver quality output. This can range from manual sorting to complex automated systems, depending on financial resources and labour costs. Regions with low-cost labour may focus on manual sorting, while those with higher budgets may adopt more advanced automated systems. In regions with highly developed waste management systems a recycling plant might rely on the sourcing of qualitatively adequate feedstock. This could as well be secured by a well-functioning informal sector plastic waste supply chain. In regions where an operator cannot rely on this an adequate pre-conditioning must be foreseen as part of the recycling plant.

One of the study's key conclusions is that open-loop technologies, while effective in managing waste in the short term, can be counterproductive for developing closed-loop recycling systems. These technologies are typically cheaper but fail to provide the high-quality recyclates necessary to sustain the plastics' value chain. As a result, down-cycling methods may hinder long-term efforts to establish sustainable, circular plastic economies.

Figure 2 shows the role of open loop and closed loop recycling in the plastic value chain. As can be seen, for open loop recycling solutions the feedstock in many cases is lost for new plastic polymer production. In exceptional cases, e.g. incineration with CCU, the feedstock can be recovered in the future, when the product reaches its end of life. In most cases this feedstock nevertheless will be released to the environment due to wear and tear or will be dumped in a landfill or will be incinerated without capturing the generated CO_2 emissions after its use phase. Such a solution can withdraw temporarily plastic waste from contaminating the environment but feeding such diverted plastic waste from open-cycle plastic recycling solutions back into the plastic supply chain may be challenging.

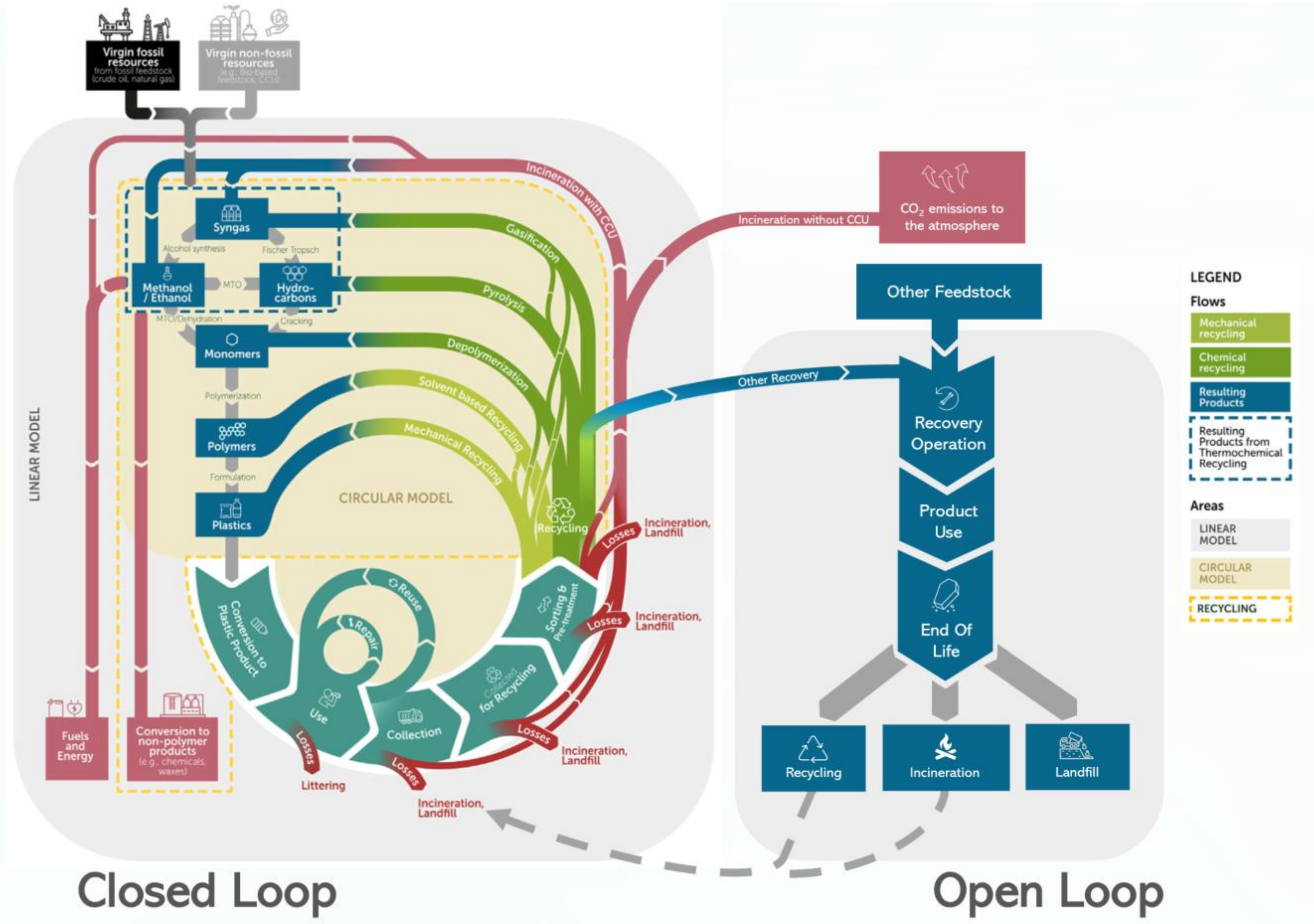


Figure 2. Plastic recycling terminology (modified) [1]

In summary, while open-loop recycling technologies play an important role in regions with limited infrastructure, they should not be viewed as a long-term solution for plastic recycling. Closed-loop recycling, although more costly and demanding higher-quality feedstock, is essential for maintaining the plastic material cycle and supporting a circular economy.

In any case, investments in improving collection systems and sorting capabilities are critical to achieving higher recycling rates and reducing plastic waste.

Setting the Context

Besides the nature of plastic as a material that is designed to endure in the environment also the sheer quantity increases and the multitude of applications of that material pose a huge challenge whenever governance structures, legal systems and organisational setups for waste management are not in place.

Figure 3 shows the increase of the global plastic production that reached a little above 400 Mio. tonnes in 2022 as well as the share of plastic that has been produced based on recycling or biobased or based on carbon capture – options that are considered as circular options. Figure 4 shows a break down by polymer of the global plastic production.

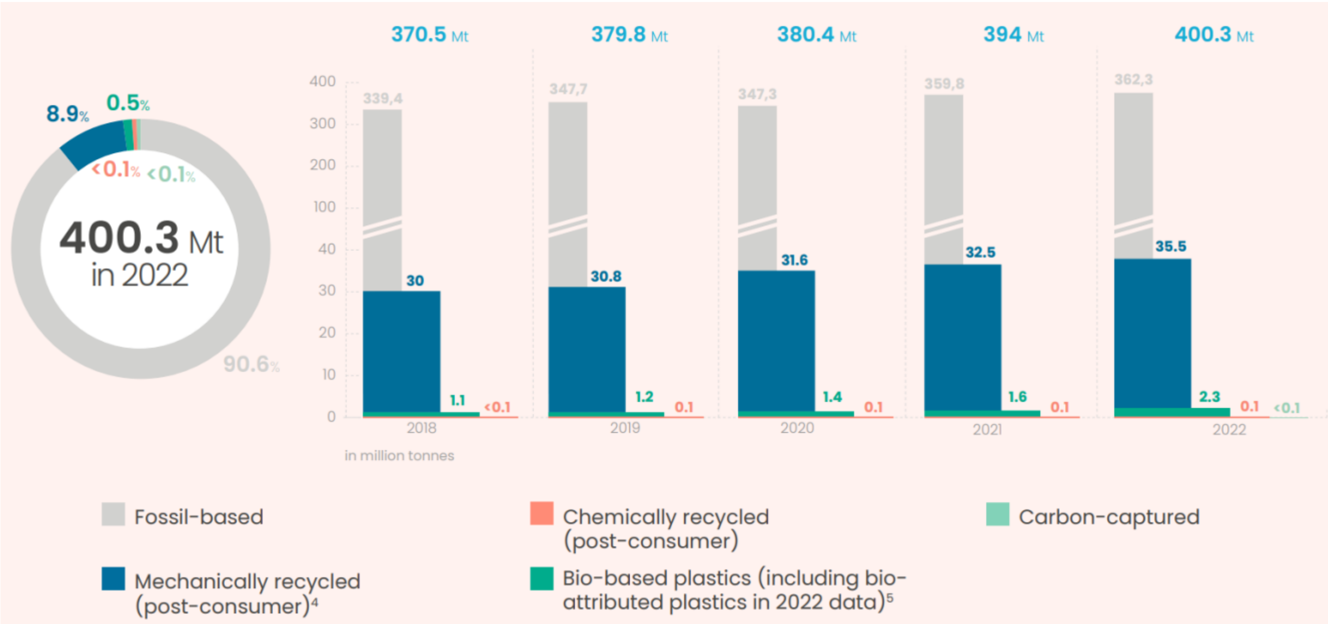


Figure 3. World plastic production, production based on sustainable alternative routes [2]

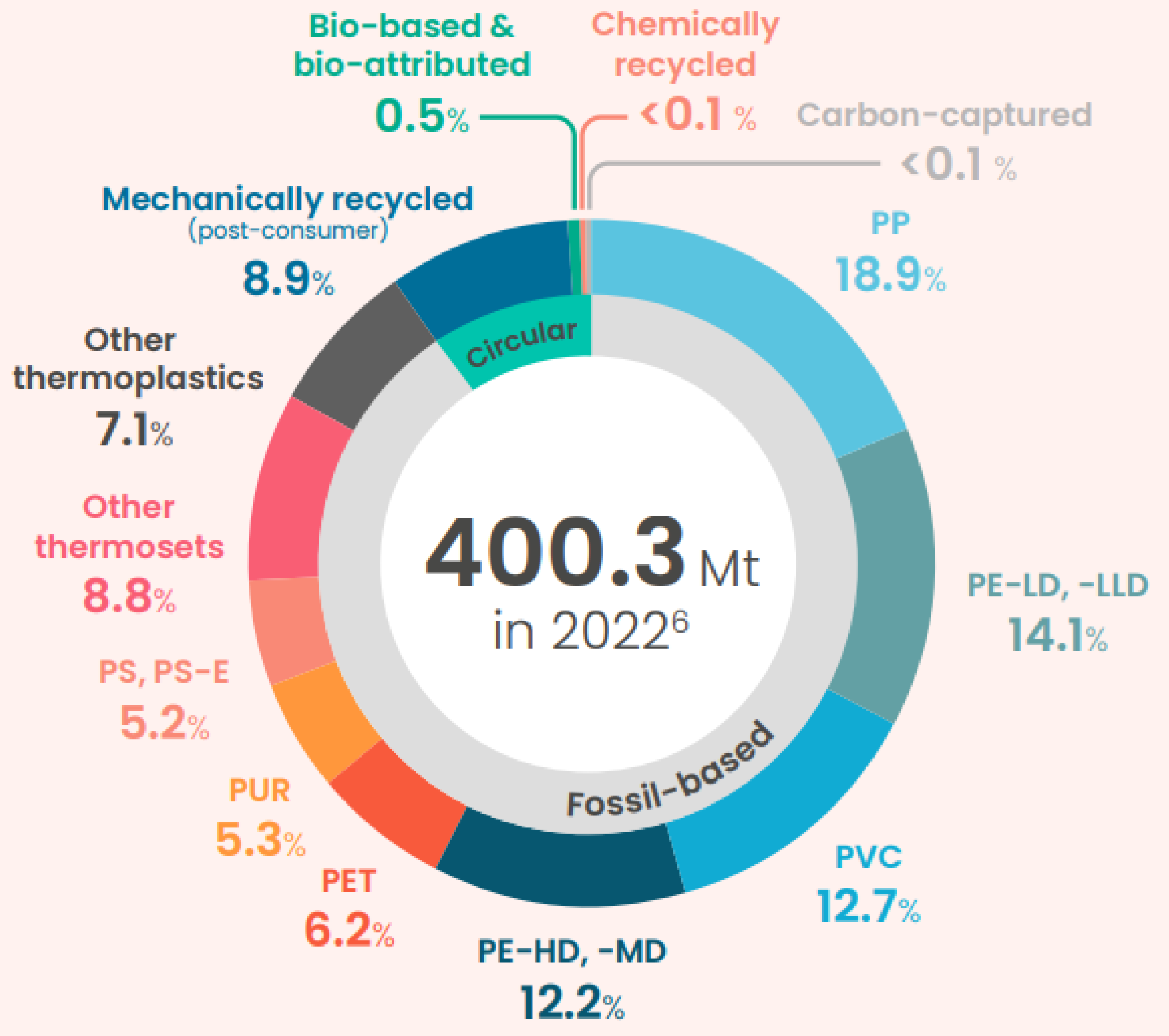


Figure 4. Global plastics production by polymer [2]

The need for a comprehensive comparative plastic recycling study for low value plastic waste

The mounting global plastic waste crisis demands a systematic and comparative analysis of diverse management strategies to identify optimal solutions. While research on specific recycling technologies and waste management systems has grown, a comprehensive assessment encompassing the full spectrum of options, particularly in the context of the Global South, remains a critical gap in knowledge. Relevant studies, which are comparing plastic recycling, have been done by CSIRO [3], ClosedLoopPartners [4], IPEN [5], JRC [6], IGES&UNEP [7], FOEN [8], DELOITTE [9] and others, but most of these studies focus on a particular plastic recycling technology segment (e.g. chemical recycling) or are focusing on a particular country, with little relevance for countries in the Global South.

This study is essential due to the unique challenges posed by developing economies. Many countries in this region lack robust waste management infrastructure and fast-growing waste quantities, leading to uncontrolled plastic waste accumulation and severe environmental consequences. A comparative analysis is crucial to inform the selection of suitable and effective plastic waste management strategies tailored to these specific conditions. Despite numerous studies [10, 11] on handling low-value plastics in Indonesia, the focus has primarily been limited to assessing local technologies without the details of implementation, recycling challenges, or waste collection recommendations. Therefore, this report combines an analysis of Indonesia's current state with an evaluation of various recycling technologies, culminating in the selection of existing businesses best suited for implementing these solutions.

By examining mechanical, chemical, and biological recycling technologies alongside alternative approaches such as the incorporation of plastic waste into construction materials, this research aims to provide a holistic understanding of the potential benefits, drawbacks, and trade-offs associated with each option. Furthermore, the study will incorporate a rigorous assessment of environmental, economic, and social impacts to enable informed decision-making.

A key focus is to bridge the gap between advanced recycling technologies, often developed and implemented in developed economies, and the practical realities of developing countries. By including "bridging technologies" that can be more readily integrated into existing waste management systems, this research seeks to offer actionable solutions for immediate impact.

Moreover, the study will consider the broader implications of plastic waste management, including issues of resource efficiency, circular economy principles, and public health. By adopting a systems-thinking approach, this research will contribute to the development of integrated and sustainable waste management strategies for the Global South.

Given the complex interplay of technological, economic, social, and environmental factors, a comparative analysis is essential to identify the most promising pathways for addressing the plastic waste crisis in these regions. By filling this critical knowledge gap, this study will provide valuable insights for policymakers, industry stakeholders, and researchers alike.

Plastic Recycling in the context of Waste Management & Circular Economy

Plastics are one of the waste fractions which still show a relatively low recycling rate. Less than 10% of plastics are currently recycled globally [12]. Figure 5 shows the point of destination of the global plastic waste by sector. As can be seen, most of the plastic still is disposed of, in managed landfills, in unmanaged dumpsites, or incinerated.

The reasons for this low recycling rate are manifold but the main challenge is that only mechanical recycling, from a technological point of view, is a mature technology and state of the art. However, mechanical recycling is by far not suitable for all types of plastic waste, as will be discussed in detail in the following chapters.

Even in developed industrial countries, like the European Union, the recycling rate of plastic with around 30% is relatively low due to economic and technological challenges. In Europe and in other industrialized countries the hard to recycle plastic waste, which is not suitable for mechanical recycling under current boundary conditions, is generally incinerated in dedicated waste to energy incineration plants or so called co-incineration plants, as Refuse Derived Fuel (RDF), or sometimes also referred to as Solid Recovered Fuel (SRF) [13].

In developing nations plastics are very frequently incinerated by open burning at landfills or near residential areas, with a high environmental impact due to toxic fumes, black carbon and microplastics release into the environment. Many efforts are directed to address that problem [14].

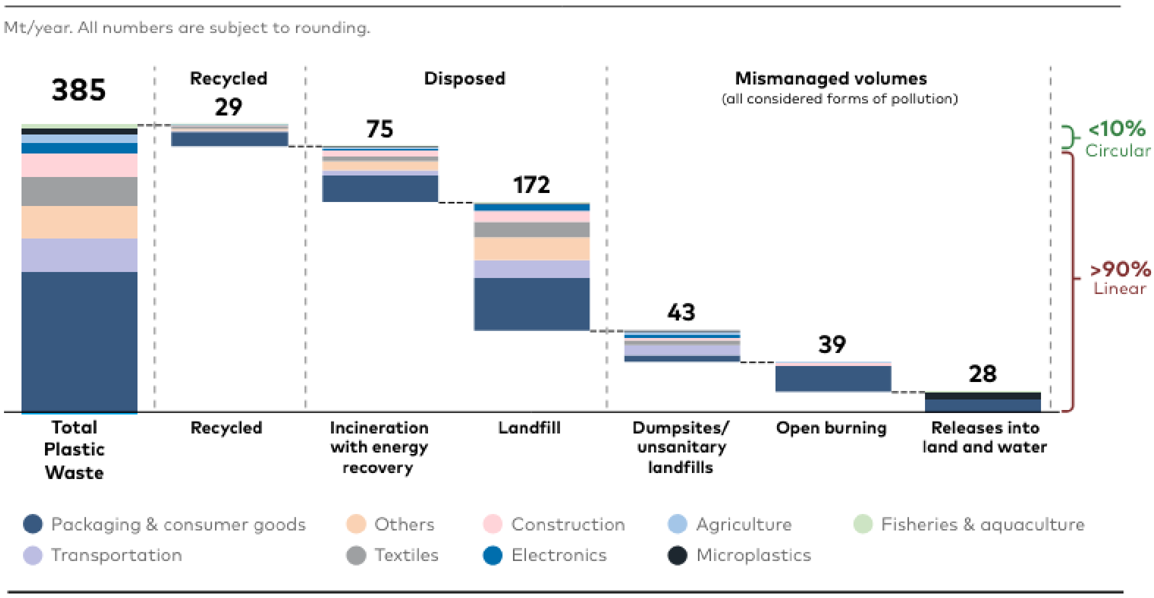


Figure 5. End-of-life fate of plastic waste in 2019 by sector [12]

One of the main reasons for plastic waste not being recycled is the issue that in many parts of the world the coverage of (separate) collection of (plastic) waste is very low. Waste that is not collected cannot be treated or recovered in the right way. In addition to mismanaged plastic waste, plastic enters the environment also due to its use in specific applications such as rubber from tires or fibers from textiles and similar applications. Figure 6 displays, based on data from the global plastics outlook database, that in 2019 22 million tonnes of plastic leaked to the environment, with 88% being macro-plastics (particles with a diameter of 5 mm or larger) and 12% as micro-plastics (particles with a diameter of <5 mm). Most of the plastic leakages stem from mismanaged waste (82%).

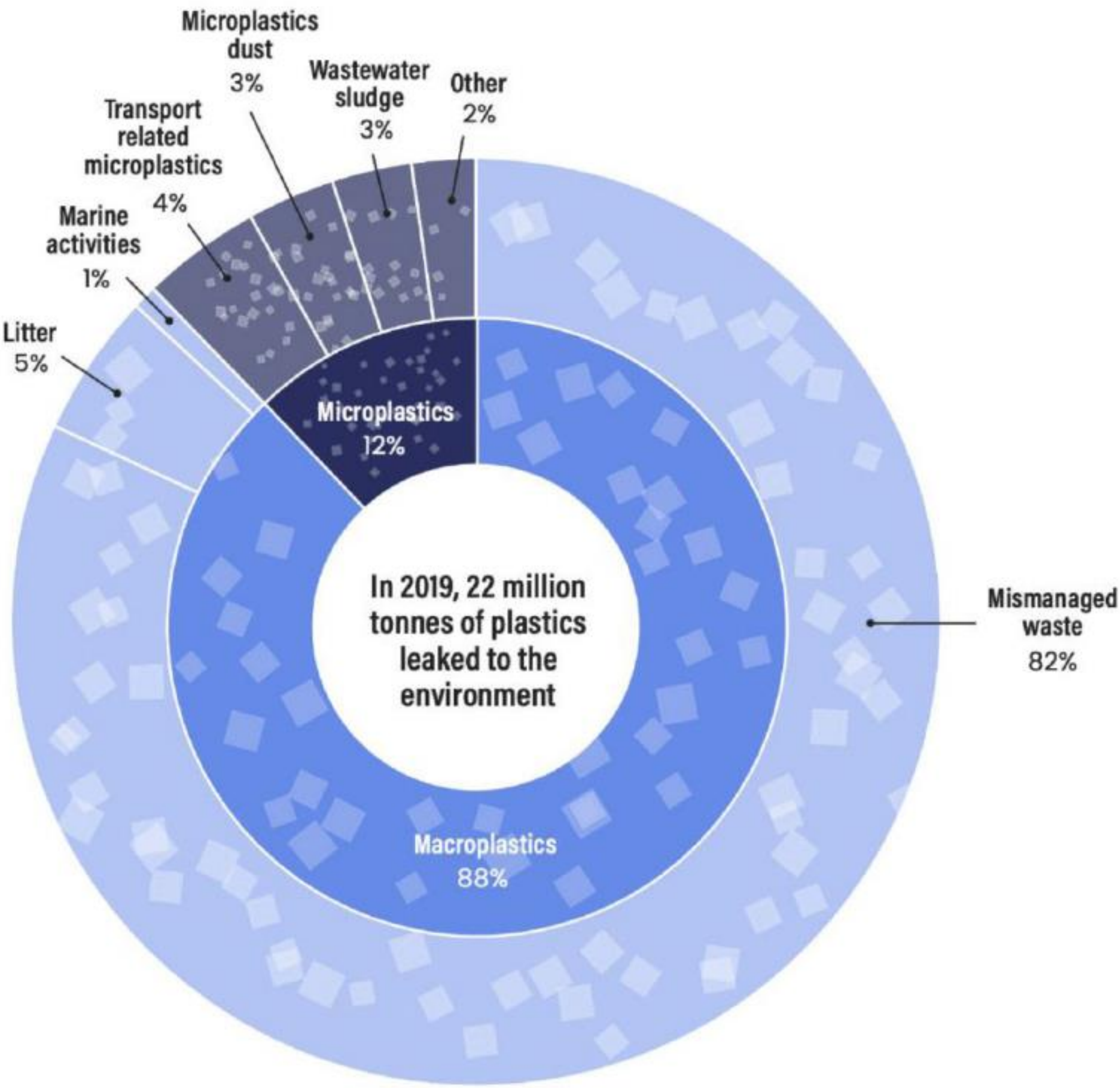


Figure 6. Plastic leakages to the environment in 2019 [15]

According to the widely used concept of the waste hierarchy (see Figure 7) waste managers may also be seen as material custodians aiming to retain the value of materials at the end of the life cycle of products manufactured from these materials.

Value retention of a material is achieved best by waste prevention and, product reuse. These options relate to level 1 and 2 of the waste hierarchy as shown in Figure 7. If prevention and reuse is not possible, recycling – level 3 - is the next best option. The concept of recycling is to use the material for its originally intended purpose – **closed loop recycling** or recycling in the narrow sense of the term – or for any other reasonable purpose – **open loop recycling**, also referred to as down-cycling. Level 4 of the waste hierarchy aims at other forms of recovery such as making use of the energy content in products.

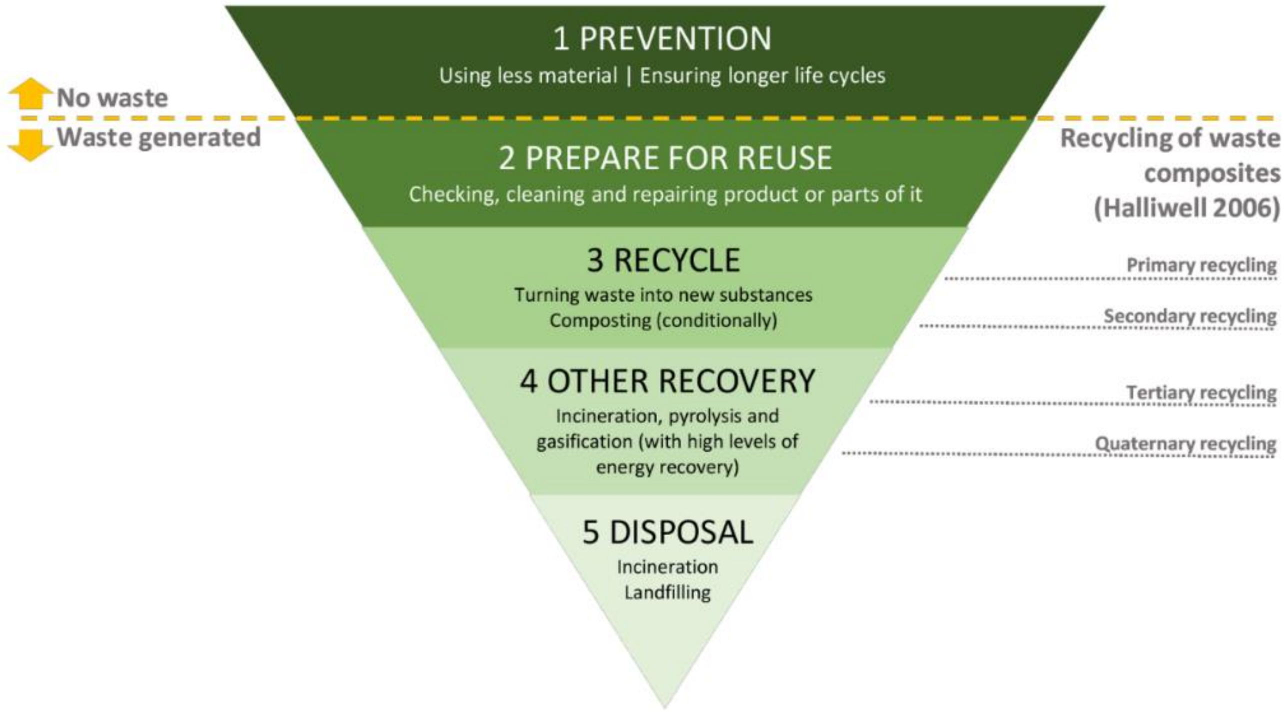


Figure 7. The Waste Management Hierarchy [16]

The differentiation between the “recycle” and the “other recovery” stage in the waste hierarchy is a little blurry and often very much influenced by the legal system in place in a certain jurisdiction. Especially in jurisdictions where mandatory recycling rates are stipulated, such as for the nations of the European Union.

The differentiation between these two stages is very important and very much under dispute as it makes a huge difference whether a certain recovery practice is accepted as a “recycle” vs. as an “other recovery” type of waste management option. For example, on the European level, chemical recycling options for plastic waste are being discussed currently whether and to what extent they are seen as a recycling option, as opposed to be classified as an “other recovery” option. This is also very relevant insofar that the product of various chemical recycling technologies is suitable to be used as a feedstock in the plastic production as well as to be used as a fuel for energetic purposes which is clearly an “other recovery” as per level 4 of the waste hierarchy, as shown in Figure 7.

There is not one single recycling technology, which from a technology or economical point of view is suitable to deal with all types of plastics in the different contexts. Plastic waste is very heterogenous in terms of its composition as well as the applications it results from, and different recycling and recovery technologies should be part of a circular economy for plastic materials, as is illustrated in Figure 8 below.

Figure 8 displays the situation of plastic waste and its management and value retention loops. The term “new recycling routes” is referring to chemical recycling technologies which are discussed in more detail in the section on **Other recovery options.**

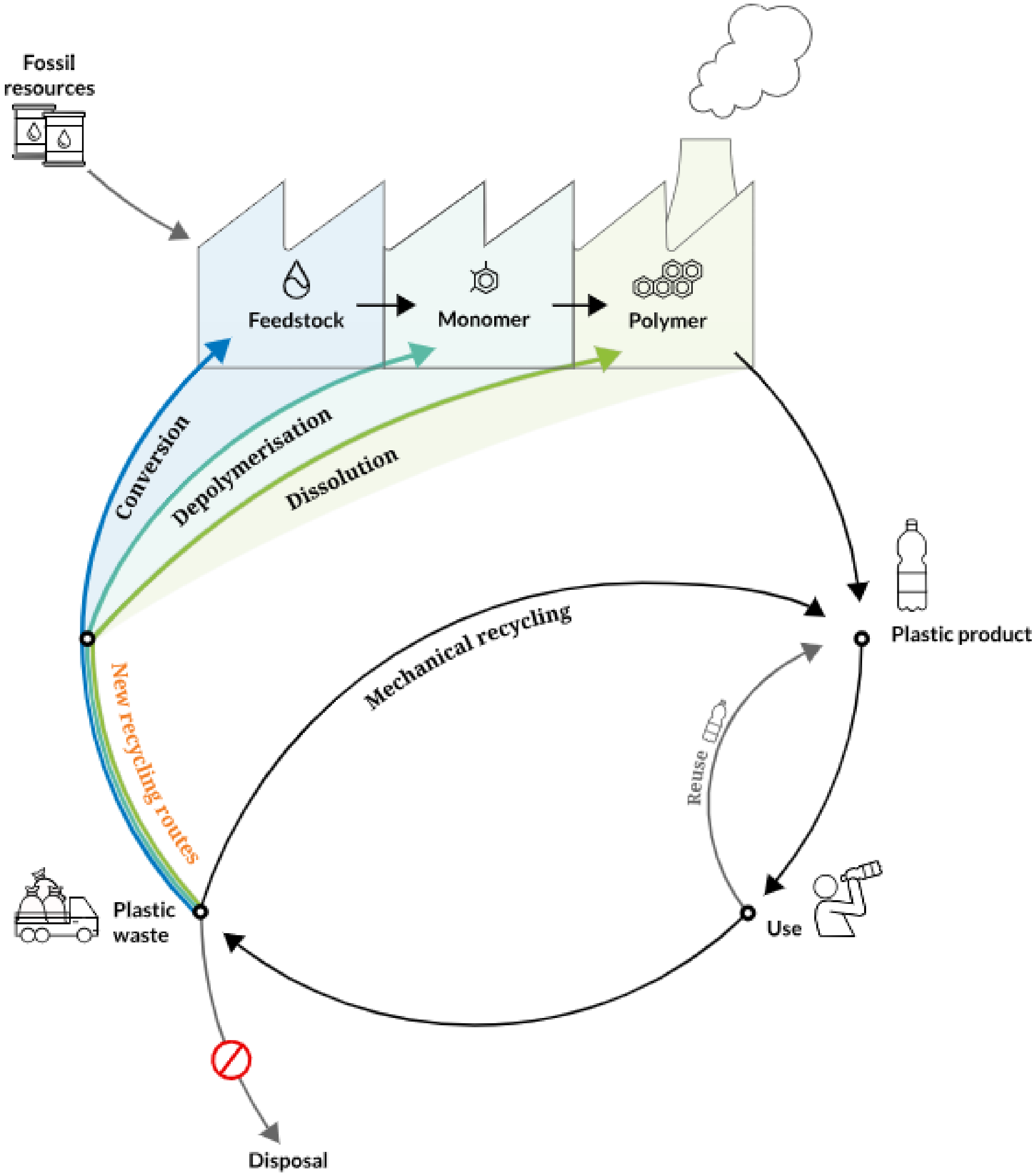


Figure 8. Role of different recycling technologies – value retention loops - in a circular economy for plastic waste [17]

Specifics of plastic

Plastic often is seen as a quite homogenous group of materials, easy to distinguish and separate from each other. But plastics are a complex group of materials and anything else but homogeneous.

New types of plastics-products are constantly developed, mixed with each other, or other chemicals are added to achieve new product qualities that enhance the performance during the use-phase of that product, but may pose problems at the end-of-life stage of these products.

Many plastic product designs combine different plastic types in layers, called multilayer plastics, to achieve a combination of specific usage properties. Therefore, we are talking about an extremely complex product group with numerous types of plastics, making recycling for some of the plastic waste streams a technical challenge. Understanding this fact is key to find proper plastic waste management and recycling solutions, and to solve the global plastic pollution problem.

The complex world of plastics

Plastics have become a material group that is used for many different applications in our modern world. Plastic as a material has many advantages during the production and the use phases, however due to its diverse uses the end-of-life phase poses a huge challenge that still needs to be addressed in the right way in many parts of the world.

As feedstock to produce virgin polymers via the fossil-based production route mainly crude oil and natural gas are used. The following Figure 9 shows the petro-chemical production routes for the most common commodity polymers.

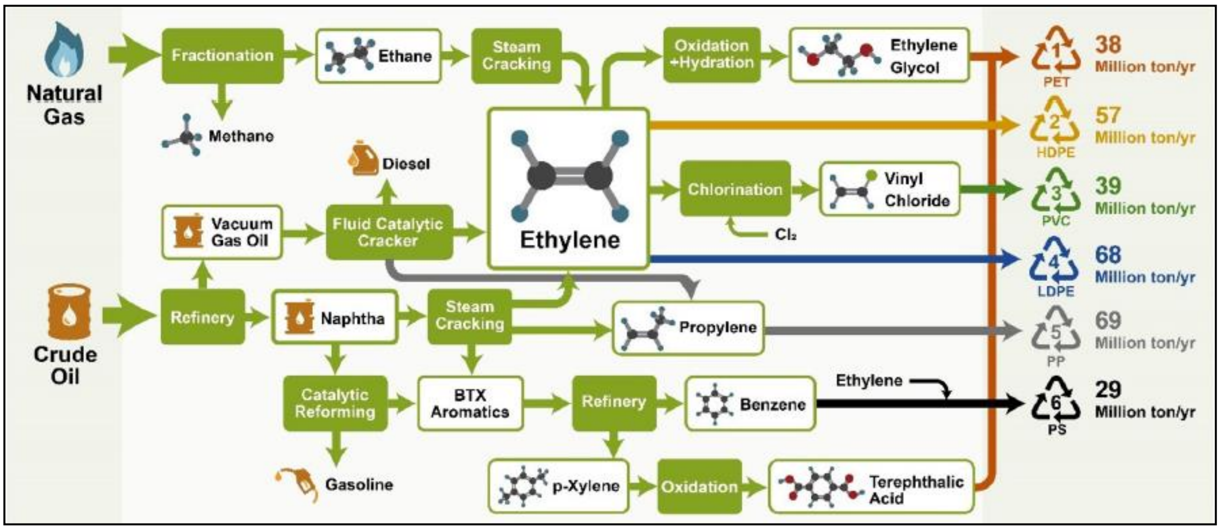


Figure 9. Supply chain for the manufacture of virgin plastics [18]

The product group of plastics is extremely heterogeneous and constantly changing, due to the development of new plastic products that are brought to the market. These new plastic types are developed by addition of specific additives and fillers, chemicals and materials added to reach certain new product properties at least cost.

There are different classification systems to group plastics. A very common way is the International Resin Identification Coding System (RIC), which is shown below in Figure 10.

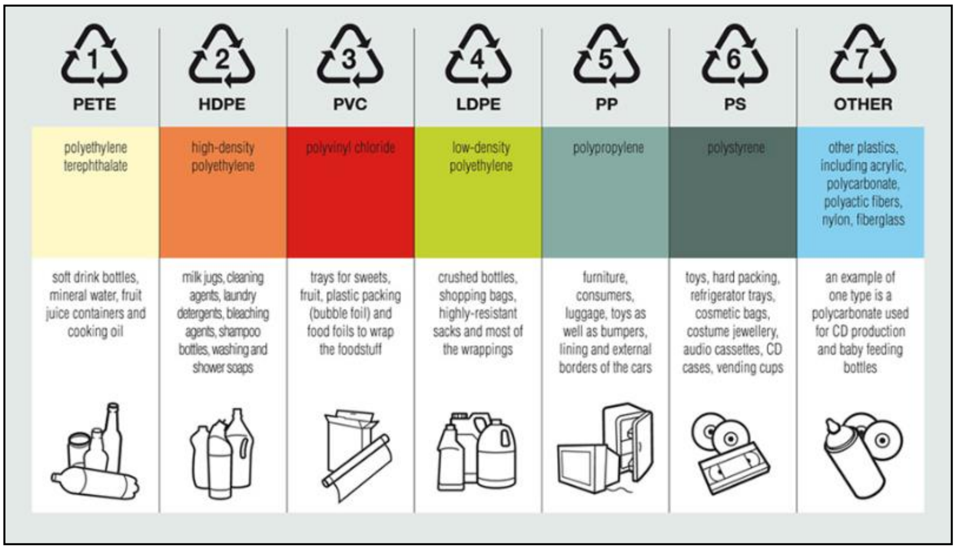


Figure 10. Resin Identification Codes for main polymer types [19]

The RIC system is the most used system and is differentiating between the most frequently plastic resin types, which are in use.

The polymers labelled 1 to 6 in Figure 10 are also referred to as **standard or commodity plastics**, which are produced in high quantities and can be seen as the primary material for the production and development for most of the plastics in use. They must be seen in contrast to **engineering plastics** or **high-performance plastics** that make up less than roughly 10% and 1% of the overall plastic quantities brought to the market (see Figure 11).

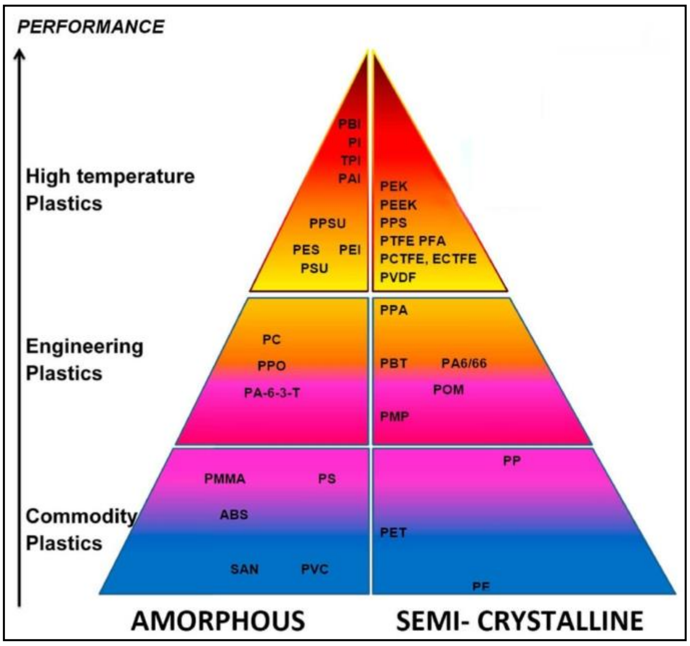


Figure 11. Commodity vs. engineering and high temperature plastics [20]

Plastics are used in a myriad of applications ranging from packaging and construction to automotive and electronics. Each application requires specific properties, leading to a diverse range of plastic types. This diversity makes it challenging to create a standardized recycling process that can handle all types efficiently and safely.

The complexity of plastics in use, with all the additives to reach certain product qualities and characteristics, are one of the key reasons why the recycling rate of plastics is still very low when compared to other waste streams like glass, metal or paper. Because of this, the design phase of plastics for recyclability is becoming an increasingly important step.

Innovations such as developing mono-material products, reducing the use of harmful additives, and creating more efficient sorting and recycling processes can significantly improve recycling rates and the quality of recycled materials.

Many types of plastic materials, including polypropylene, polystyrene, polyvinyl chloride, high-density polyethylene, low-density polyethylene, and polyurethanes, can be recycled using both chemical and material recycling methods. However, the diverse physical and chemical properties of plastic waste make its separation a challenge. Therefore, reliable and effective plastic waste separation technology is crucial for enhancing the value and recycling rate of plastic waste.

Figure 12: Different types of plastics are often not separated

Integrating recycling with advanced separation technologies would be an efficient approach to reducing environmental contamination from plastic waste, particularly in industrial applications [21]. This is especially true in developing countries, where a proper integrated waste management infrastructure often is missing, and where the complexity of different plastics in circulation makes appropriate recycling of plastics often a challenge, as will be discussed in subsequent chapters.

Thermoplastics versus thermoset plastics

Looking at the recyclability of plastics provides an important differentiation between two main groups of plastics: i) thermoplastics which can be re-melted, and ii) thermoset plastics which cannot be re-melted after curing.

Thermosets are typically used in applications where heat resistance is required, whereas most plastics in daily applications, e.g. packaging or for consumer products, are made of polymers belonging to the group of thermoplastics.

During the production process of thermosets plastics, the curing process induces non-reversible chemical reactions that cross-link polymer chains, making thermoset plastics resistant to melting at high temperatures and providing superior mechanical strength. This fact makes recycling of thermoset with traditional recycling processes, like mechanical recycling, rather difficult. These plastics also maintain their shape and do not deform in cold temperatures, allowing them to perform well in environments with extreme temperature variations. Additionally, thermoset plastics can be produced at a low cost and enhanced by combining them with fibers like carbon, glass, or aramid to create thermoset-based composites. Their high thermal, chemical, and mechanical stability makes them ideal for structural and protective applications, such as in wind turbines. Most of the thermoset and thermoset-based composite waste is sent to landfills due to the challenges associated with recycling these materials.

Figure 13 below shows typical polymers belonging to the thermoset and the thermoplastic groups.

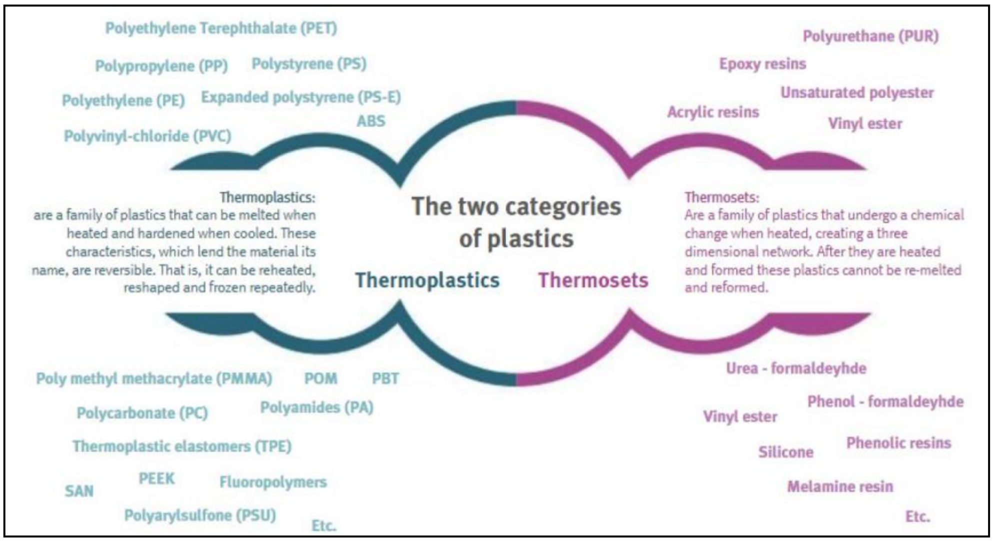


Figure 13. Thermoset and Thermoplastic Plastic Groups [22]

Thermoplastics can be recycled more efficiently through processes such as mechanical recycling, which involves shredding, melting, and remolding, as will be discussed later in this document in more detail. This process is less energy-intensive compared to the chemical recycling methods required for thermosets, making thermoplastics in general a more cost-effective option for recycling.

Bioplastics as a part of the plastic material group

The urgent plastic pollution problem did also incentivize the development of materials that are supposed to be more sustainable to replace fossil based plastic feedstocks with renewable based materials, like biomass.

This material group is called Bioplastics and currently are covering a small share of approx. 0.5 % of the global plastic production. Bioplastics can be either bio-based, biodegradable, or a combination of both. Nearly half of all bioplastics, despite being derived from renewable resources, are not biodegradable.

These bioplastics, often referred to as 'drop-in' solutions due to their identical chemical structure to existing fossil-fuel based plastics, include bio-polyethylene (bio-PE), bio-polyethylene terephthalate (bio-PET), and bio-polyamides (bio-PA). Bio-based materials or products are those derived, at least in part, from renewable biomass feedstocks. This biomass encompasses organic matter from living organisms such as corn, sugarcane, cellulose found in trees, and even algae.

Figure 14 displays the global production capacities of bioplastics and the forecasted growth of the capacities. Still – despite of the forecasted more than tripling capacities over the next few years – bioplastic production will hardly exceed 1 % of the global plastics production.

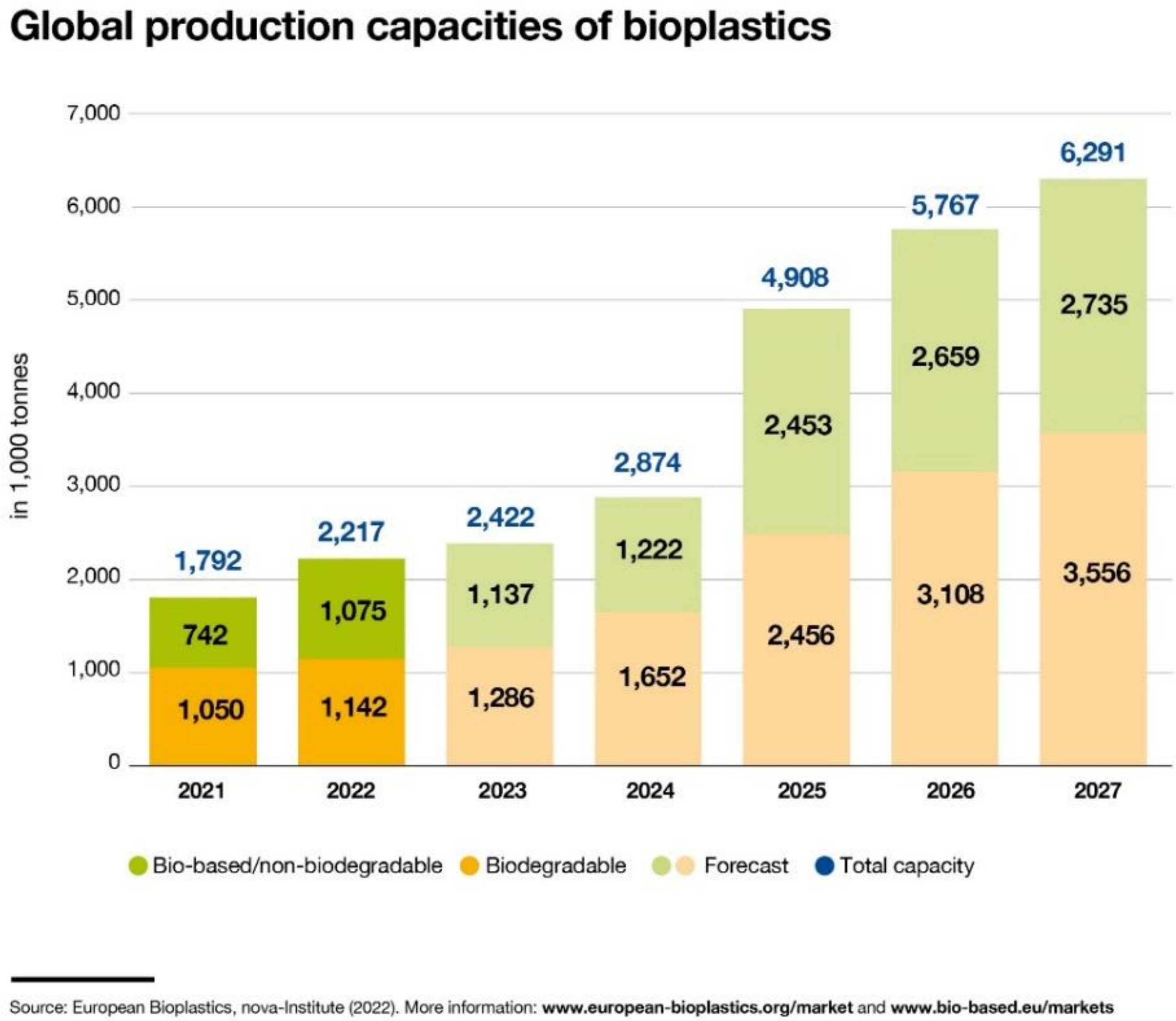


Figure 14. Global production capacities of bioplastics [23]

Biodegradability describes a natural process where microorganisms in the environment, primarily bacteria and fungi, transform a material into simpler substances. These end products are harmless to the environment, consisting of water, carbon dioxide, and even microbial biomass that can become nutrients. The key point is that the origin, whether natural or synthetic, does not determine biodegradability. Instead, the molecular structure of the material dictates how easily microorganisms can break it down [24].

In Figure 15 a simple structure of the different plastic types, fossil-based and bio-based is provided. This overview allows an easier differentiation between biodegradable and non-biodegradable plastics and shows that there is fossil-based plastic that is biodegradable, and that there is also bio-based plastic that is not biodegradable.

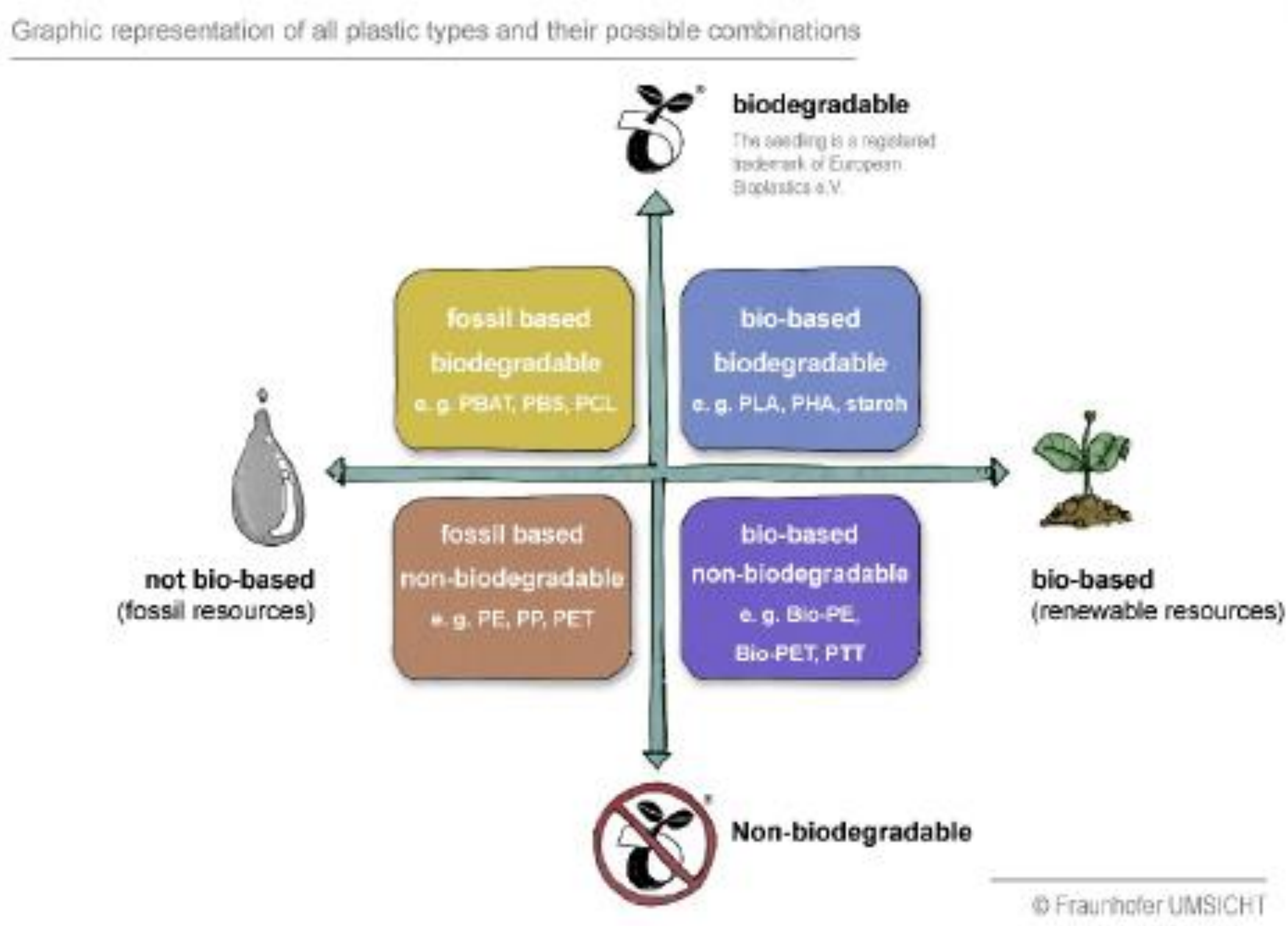


Figure 15. Fossil and bio-based plastics and their biodegradability [24]

Biodegradability is also a matter of certain physical conditions needed by the microbes to degrade plastics. This is among others that a certain temperature is kept over a certain amount of time, oxygen and water needs to be available in the required form as well. If these conditions are not met even biodegradable bioplastics will not be bio-degraded and will remain as plastic fragments in natural environments [25].

Another degradation mechanism that is causing the formation of microplastic in natural environments is oxo-degradation. This process describes the fragmentation of plastics due to UV-radiation, heat and oxygen. The degraded plastic largely remains in the environment as microplastics. In many countries these types of plastics have been banned from use in the packaging sector however they are still used in agriculture for mulching as well as for coating or specific fertilizer products. These applications therefore eventually lead to a microplastics release to the environment.

Plastic additives and other plastic components

In most plastic materials used for various products, the base polymer is combined with additives to create a plastic compound. These additives are chemical compounds added to enhance the performance during shaping processes like injection molding, extrusion, blow molding, vacuum molding, etc., and to improve the functionality and aging properties of the polymer, as well as to reduce the cost of the final compound. The common additives used in different types of polymeric packaging materials include:

- **Functional Additives**: These include stabilizers, antistatic agents, flame retardants, plasticizers, lubricants, slip agents, curing agents, foaming agents, and biocides. Each serves a specific role in enhancing the functional properties of the final plastic product. For example, flame retardants enable the use of polypropylene (PP) in electronics, construction, and transportation by reducing flammability.
- **Colourants**: Such as pigments and soluble azo colourants, which provide a variety of colours to the plastic products.
- **Fillers**: Materials like mica, talc, kaolin, clay, calcium carbonate, and barium sulfate, which are added to reduce cost, improve stiffness, or modify other properties of the plastic.
- **Reinforcements**: Such as glass fibers and carbon fibers, which enhance the mechanical strength and durability of the plastic.

Each type of additive plays a crucial role in modifying and enhancing specific properties of plastic materials, ensuring they meet the desired performance requirements for different applications. It is important to note that in almost all cases, additives are not chemically bound to the plastic polymer, what means that they are leaching into the environment constantly if their release is not contained. E.g. during its use phase, in landfills, during recycling or incineration. Only reactive organic additives, like certain flame retardants, undergo polymerization with the plastic molecules and become integrated into the polymer chain [26].

There are numerous additives, which are used in the production of plastics. And their number is growing continuously because new plastic types are developed [27] to increase the array of applications for that material.

Below a short description of the most used additives in the production of plastics is given [26].

- **Plasticizers:** Plasticizers are primarily employed to enhance the flexibility, durability, and stretchability of polymeric films, while also reducing melt flow during production. They improve impact resistance in the final plastic film and impart soft and adhesive properties to the material. The most common group of chemicals used as plasticizer is the group of phthalates.
- **Antioxidants:** Antioxidants are incorporated into different polymer resins to mitigate oxidative degradation of plastics, particularly when exposed to ultraviolet (UV) radiation. They function by neutralizing highly reactive free radicals generated by heat, radiation, and mechanical shear, which can accelerate polymer degradation. In applications like food packaging, where plastics are exposed to high temperatures such as infrared heating, retort processing, and microwave heating, the risk of oxidation increases.

- **Heat stabilizers:** Heat stabilizers are crucial additives that prevent thermal degradation of polymers when exposed to high temperatures, particularly during thermal processing of foods. Polymers such as PVC, PVDC, vinyl chloride copolymers (e.g., vinyl chloride/vinyl acetate), and PVC blends require heat stabilizers to maintain their functional properties. In contrast, polymers like LDPE and polyamides can withstand severe heat conditions without the need for heat stabilizers, as they inherently exhibit good thermal stability.
- **Slip Agents:** Slip agents, also known as slip compounds, play a crucial role in reducing the surface coefficient of friction of polymers. They provide lubrication to the film surface and offer several other benefits, including imparting antistatic properties, facilitating better mold release, lowering melt viscosity, and preventing sticking. Commonly used slip compounds include fatty acid amides (such as primary erucamide and oleamide), fatty acid esters, metallic stearates (like zinc stearate), and waxes.

Figure 16 illustrates the share of different additives, which are used in the global plastic production.

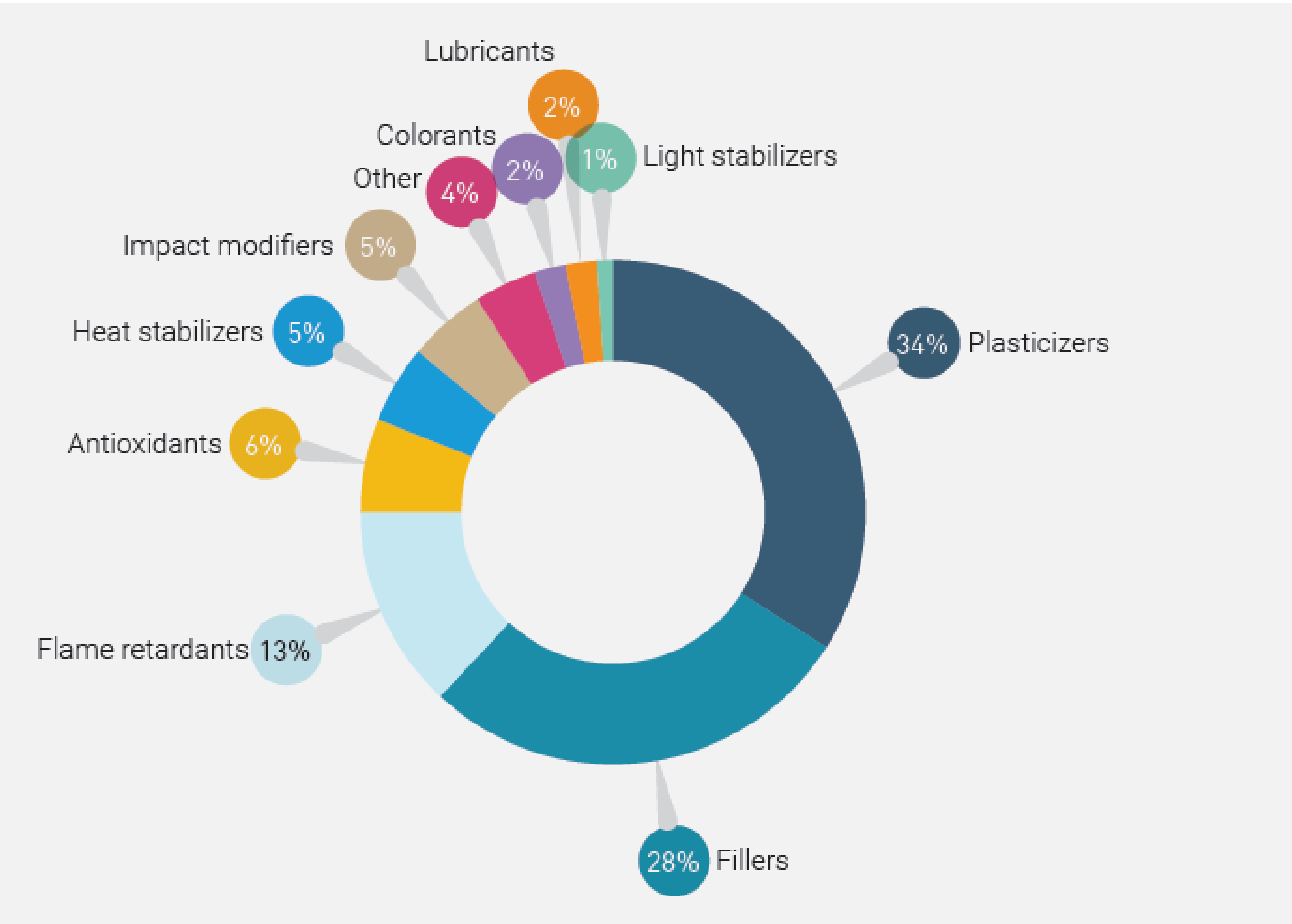


Figure 16. Share of main additive types in the global plastics production from data covering the period 2000–2014 [27]

Which additives are used in a specific marketed plastic compound largely depends on the final application that the compound is aimed for. Therefore, if certain plastic waste is kept separate from the other plastic waste in the end-of-life stage the contamination of recyclates by certain additives can be reduced.

While additives make up just a small percentage of a specific plastic compounds, fillers can make up a bigger share of the overall compound. The prevalence of either of these substances very much influences the potential effects to humanity and the environment as well as to recyclability of the respective compounds.

Migration of additives and other potentially toxic substances through the plastic recycling chain

The emissions of additives and other potentially toxic substances, like heavy metals or other contaminants, from plastic products into air, water, and soil can occur throughout all stages of the product's lifecycle. This is illustrated in Figure 17 and Figure 18 for the plastics production and recycling value chain. Assessing the magnitude and nature of these emissions is complex and depends on numerous factors. The fate of the polymer product, the substances released, any degradation by-products, and their persistence in different environmental compartments, as well as their potential for bioaccumulation, all influence human and environmental exposure over both short and long term.

In essence, the composition of non-polymeric substances within the plastic determines what can be released in the first place. However, factors like migration potential — such as how readily substances become available or dissolve during leaching — also play a crucial role in determining the actual release potential into surrounding mediums.

Furthermore, additional considerations are necessary when assessing the risks to different receptors, such as animals, humans, and habitats. The mere presence of substances in plastics or their release does not automatically equate to hazard; the actual risk depends on various factors including exposure routes, toxicity, and potential for accumulation in the environment or organisms [26].

This topic is of extremely importance for any plastic recycling or plastic disposal route to ensure that harmful chemical additives in plastic are contained and do not pose a danger to human health or the environment.

Several potentially toxic substances, including toxic metals, Brominated Flame Retardants (BFRs) and Persistent Organic Pollutants (POPs) could potentially be released or in the case of Polycyclic Aromatic Hydrocarbons (PAHs) even formed during various recycling processes. This risk is particularly high in developing countries, where sorting, reprocessing, and recycling conditions are often uncontrolled. These stages are crucial as they significantly influence the final quality of the recycled material [26].

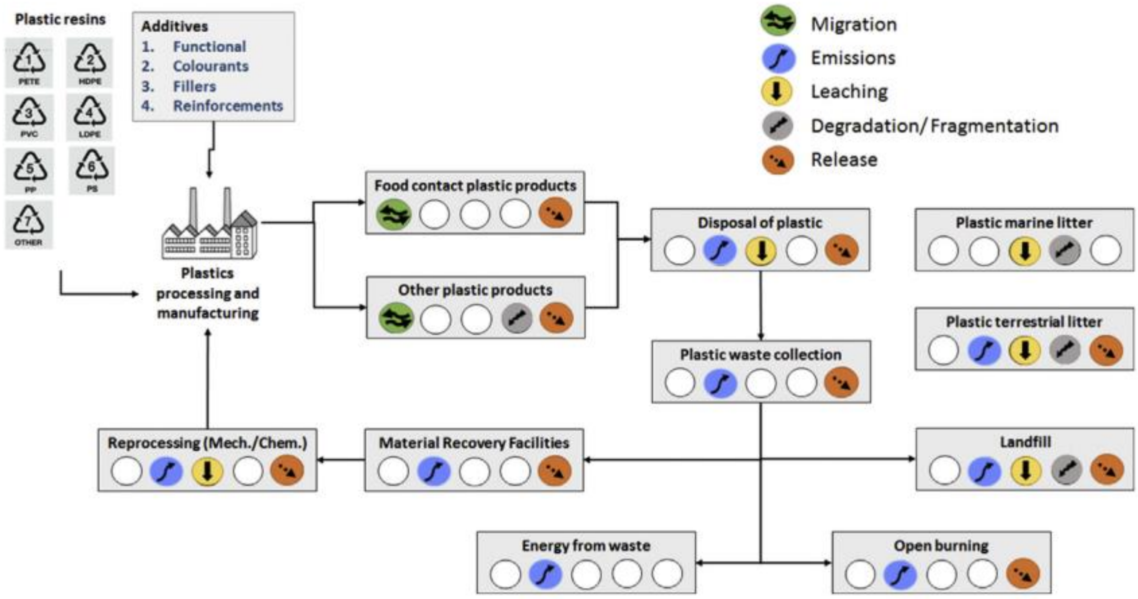


Figure 17. Migration & Emission routes of plastic additives [26]

Recycled PET has been widely used in food contact applications for over 20 years, particularly for beverage bottles. Advanced bottle-to-bottle recycling processes have incorporated decontamination methods to reduce chemical contamination. However, recycled PET can still contain chemical contaminants introduced during use, waste handling, and recycling, which can migrate into packaged beverages, if this aspect is not being taken care of during the recycling process. The presence of recycled content has been linked to the migration of carcinogenic chemicals such as benzene and styrene, as well as endocrine-disrupting chemicals like bisphenol A (BPA) (see Figure 18).

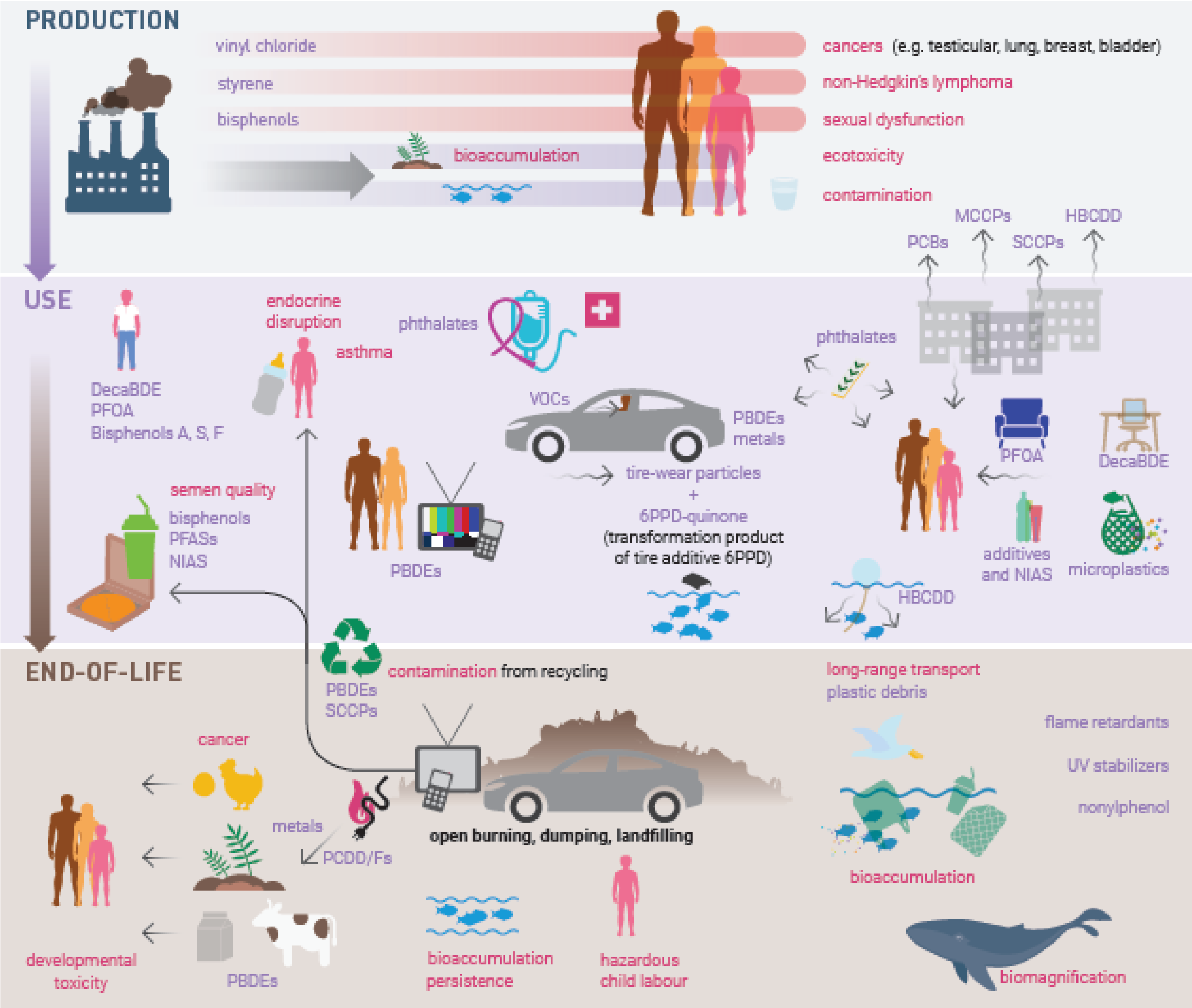


Figure 18. Pathways for ecosystem and human exposures to plastic-associated chemicals along the plastics life cycle [27]

Research comparing chemical migration from virgin and recycled PET bottles is relatively limited, this is partly due to the often-unknown proportion of recycled PET content in beverage bottles. Recent efforts have focused on developing untargeted screening methods and machine learning algorithms to effectively differentiate between virgin and recycled PET content. These methods have identified hundreds of Volatile Organic Compounds (VOCs) associated with plastic, food, and cosmetics, revealing significant differences between virgin and recycled PET, as well as variations based on the geographical origin of the recycled material.

These innovative studies are providing valuable data on the chemicals present in recycled PET and other polymers. The challenge now lies in determining how to effectively assess and manage these chemical contaminants to ensure the safety and quality of recycled PET used in food contact applications.

Compared with recycled PET, there is even less information available on the chemical migration from other mechanically recycled polymers. This lack of data presents challenges in assessing the safety and quality of these recycled materials, particularly when they are intended for use in food contact applications. Understanding the chemical migration from these materials is crucial to ensure that they meet safety standards and do not introduce harmful contaminants into the products they encase. Therefore, more research is needed to fill this knowledge gap and to develop effective decontamination and assessment methods for a broader range of recycled polymers [26].

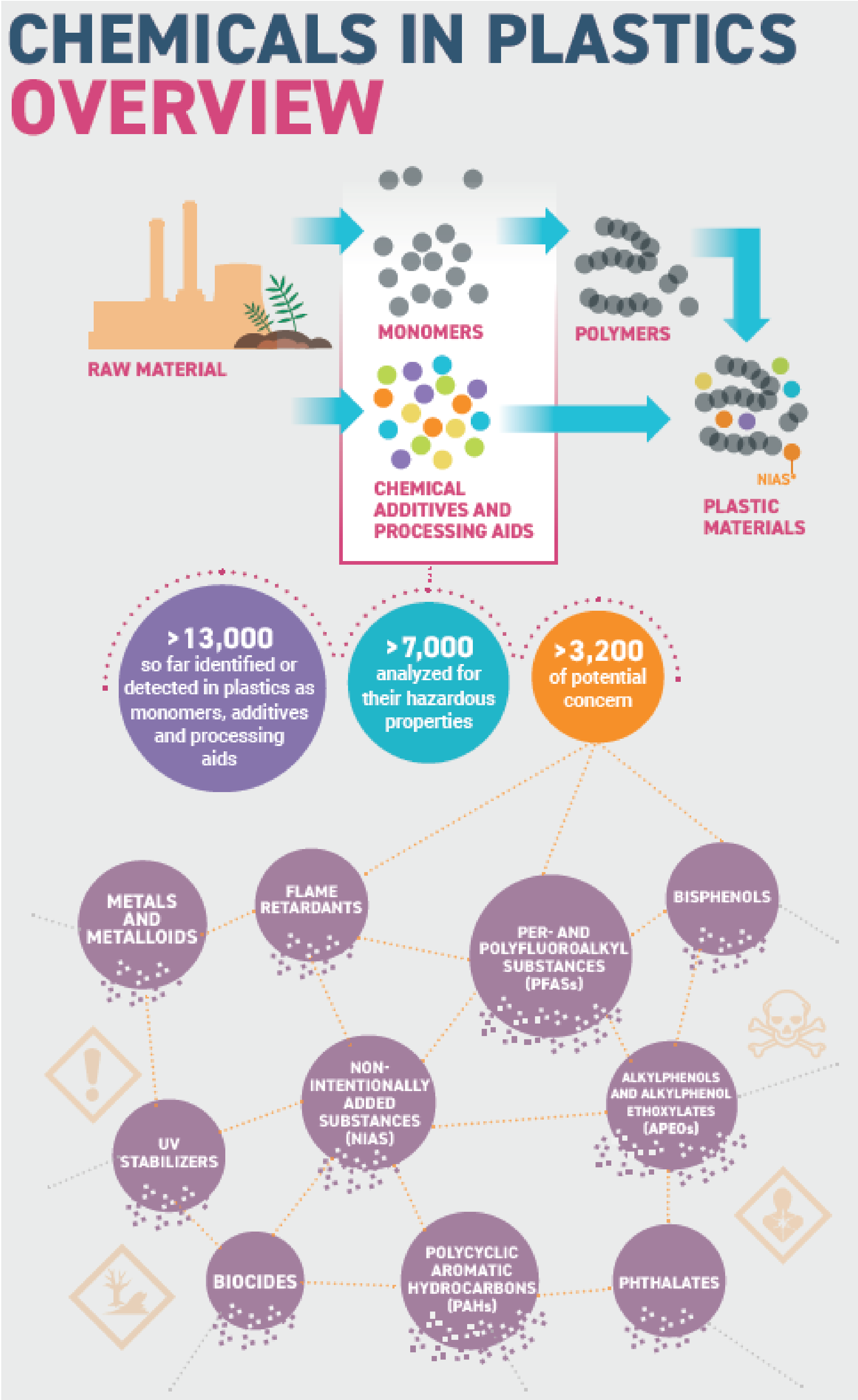


Figure 19. Overview of chemicals associated with plastics, including ten groups of chemicals identified as of concern [27]

Of special concern is the fact that from the thousands of chemicals used in the plastic production process, just for a portion of them health & environmental safety analysis have been performed to understand their impact on human health and ecosystems. This is illustrated in Figure 19. From more than 13,000 identified chemicals in plastic production just around 7,000 have been analyzed and out of them more than 3,200 are of concern. This clearly shows that it is very likely that more chemicals, which are used in plastic production, and which are leaching out into the environment, provoke health issues, but are not yet identified. In addition, plastics manufacturers are not yet forced to fully lay open what type of additives they use.

Investigations of recyclates have shown that often some chemicals remain in the recyclates, this is shown in Figure 20 for recyclates that have been investigated in many countries throughout the globe.

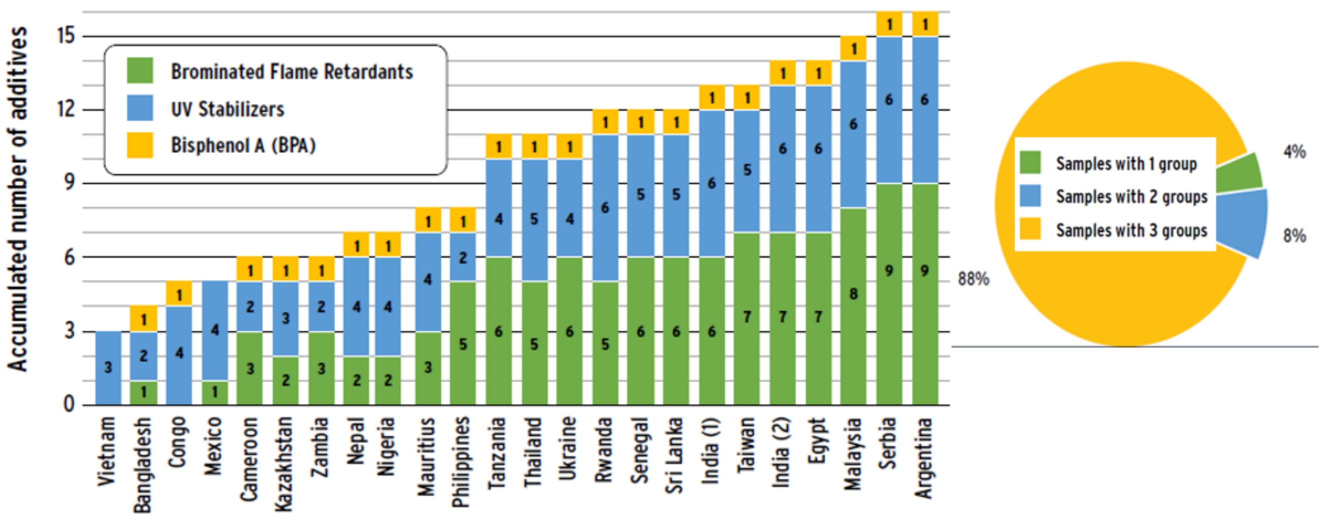


Figure 20. Overview of chemicals associated with plastics, including ten groups of chemicals identified as of concern [27]

Low value plastics (LVP)

Low Value Plastics (LVP) in the context of this study are defined as plastics for which the costs associated with their collection and processing exceeds the revenue generated from recycling them. This classification often includes a variety of plastic types and polymers, but it is context-specific; what is considered low value in one region may have value in another as markets for recycled goods evolve over time based on adequate boundary conditions that need to be put in place by establishing and implementing a supportive regulatory framework [28].

Characteristics of LVPs are:

- **Economic Viability:** The primary characteristic of LVP is that the economic costs of recycling them — such as collection, sorting, and processing — are greater than the potential market value of the recycled materials. This results in a lack of incentive for waste pickers and recyclers to handle these materials, leading to high rates of disposal at landfills or dumpsites or open burning resp. thermal treatment wherever respective infrastructure has been established already. Mandatory recycling rates, minimum recyclate content in products or financial incentives such as a premium for recyclates are potential interventions that may enhance the economic viability of plastic recycling.

Flexible plastic products (2-dimensional products) such as films, sachets and so on with a high volume to weight ratio are especially problematic as the low plastic mass involves high costs for collection, sorting and recycling per kg of these plastic wastes. According to latest research 56 % of the emissions from plastic waste stem from flexible plastics in Lower-Middle-Income Countries [29].

- **Recycling Challenges:** Many low-value plastics are made from multiple layers of different materials, which complicates the recycling process as physical separation by sorting or other mechanical processes is not possible. For instance, Multi-Layer-Products (MLPs) require energy-intensive methods to separate their components, making recycling both costly and inefficient. Consequently, these plastics are often downcycled into lower-quality products allowing for a polymer mix rather than being recycled back into food-grade materials with exact specifications.
- **Environmental Impact:** LVP contributes significantly to global plastic waste, with millions of tonnes ending up in landfills, dumpsites and the environment each year. They do not degrade easily, however, due to their low thickness (2D) are easier broken down by physical effects such as abrasion as well as oxo-degradation when compared to rigid plastic products (3D) leading to the formation of microplastics that can contaminate soil and waterways, posing risks to wildlife and human health.

In the Indonesian context, and according to a study carried out by the University of Indonesia, LVP's are categorised as such due to the difficulty to recycle and recover the material because of the differences in properties between layers, referring to multilayer plastic containers, as well as the contamination of other waste, mostly organic, coming into contact with the plastic material, due to the need of incorporating additional steps like washing and cleaning [10]. LVP in Indonesia are primarily flexible plastics that are difficult to recycle due to their mixed materials and low economic value.

Some common examples include:

- Single-use Plastic Bags - These lightweight bags mostly made from LDPE are widely used but rarely recycled due to their low value and contamination from other waste [11].
- Sachets and Wrappers - Condiment sachets, candy wrappers, and other small flexible packaging are often made from multi-layered materials combining plastics with aluminium or paper. This makes them nearly impossible to recycle effectively [30].
- Plastic Films and Wraps - Thin plastic films used for food packaging are usually not accepted in recycling programs in Indonesia, contributing to landfill waste.
- Multi-layered Packaging - Snack bags, juice pouches, and other multi-layered packaging are challenging to recycle as they are made from several layers of different materials. The growing use of these low-value plastics in Indonesia poses a significant challenge for the recycling industry, as the costs associated with collecting, sorting, and processing them exceed the potential revenue from recycling. This leads to high rates of landfill disposal and ocean pollution from mismanaged plastic waste.

Additionally, and considering the economic perspective of recycling, it has been reported that multilayer packaging is not an attractive material to the informal waste managers – waste pickers - due to their low selling price, as well as its low weight [10]. In terms of the available recycling practices specifically targeting LVPs, it has been reported that several research efforts have been carried out, resulting in the introduction of multilayer packaging as road construction materials, mixed with sand and cement, or as an input for the generation of recycled PE through chemical recycling [10, 31, 32].

On the importance of collection and sorting

The collection and sorting of plastic waste are crucial steps in managing the waste. Only what is collected may be sorted and only fractions that are sorted according to the requirements of the respective recycling process can be recycled.

Figure 21 displays the interplay of the collection, sorting and recycling stage. For example, if the collection efficiency and the sorting efficiency are each 58% and the recycling efficiency is 78% the overall system efficiency is just above 26% as the overall efficiency is derived as a multiplication of the sub-efficiencies of the sub-processes involved in the overall intervention. This means that out of 100% of plastic waste the yield of recyclates is just a little above 26%. To reach for example, the EU goal of >50% of recycling rate the individual performances of the collection, sorting and recycling stage must rise above 80% to achieve the set goal.

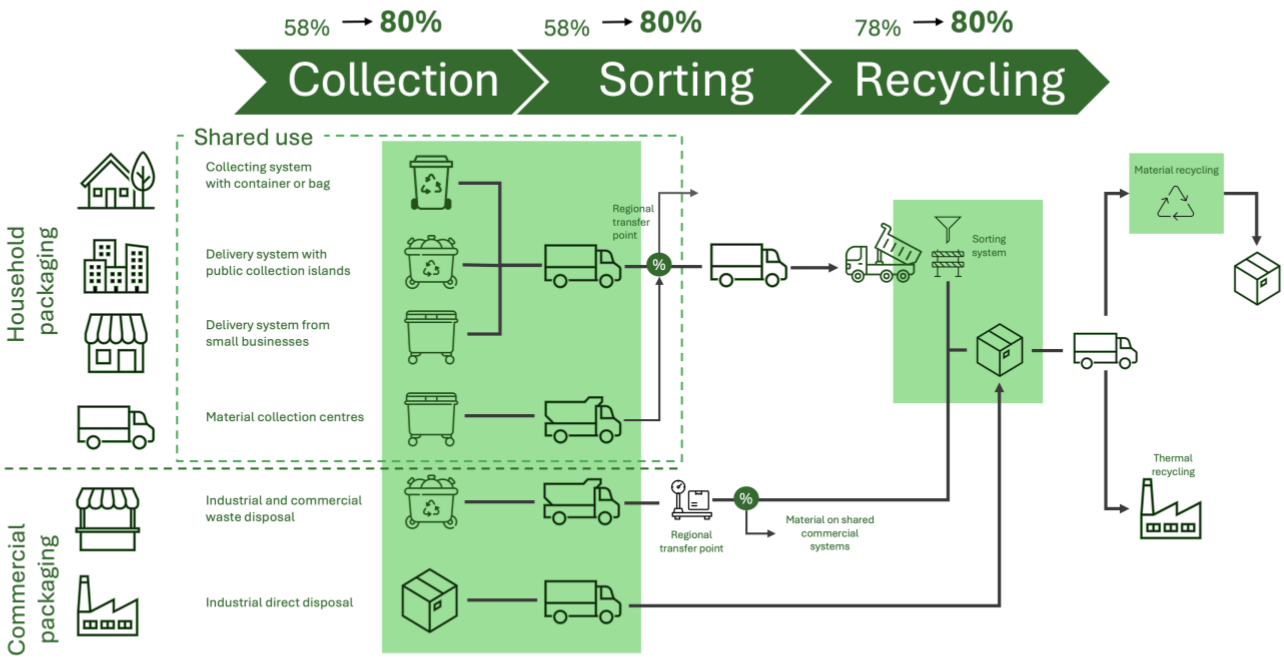


Figure 21. Overall system performance is determined by the efficiency of collection, sorting and recycling [33] (translated)

Effective collection ensures that plastic waste is gathered efficiently, preventing it from polluting the environment and entering landfills. A functioning sorting stage enables closed loop recycling instead of other recovery options.

Plastic waste collection

Effective plastic waste collection systems are fundamental, acting as the initial step in managing plastic waste sustainably and making the waste available for recycling. These systems ensure that plastic waste is systematically gathered from various sources, such as households, industries, and public spaces, preventing it from entering natural environments and contributing to pollution. The importance of robust collection systems cannot be overstated; they enable the segregation of plastic waste based on type and quality, which is critical for efficient recycling. Proper collection and sorting enhance the purity of the recyclable material, improving the efficiency and output quality of subsequent recycling processes, irrespective of the recycling technology used.

However, several challenges hinder the efficiency of plastic waste collection systems. In many regions, especially in developing countries, infrastructure for waste collection is often inadequate or non-existent. This leads to significant amounts of plastic waste being improperly disposed of in landfills, waterways, and open spaces. Additionally, the lack of public awareness and participation in waste segregation at the source exacerbates the contamination of recyclable plastics with organic waste and other non-recyclables. Economic factors also play a role, as the cost of establishing and maintaining comprehensive waste collection systems can be prohibitive without adequate funding for example through an Extended Producer Responsibility (EPR) scheme and / or government support. Addressing these challenges requires a combination of public education, investment in infrastructure, and policy interventions to create an integrated and efficient plastic waste management system.

Appropriate collection systems also allow for the separate collection of various fractions of plastic waste. By that means it can be secured to keep specific pollutants that either result from the use phase of products or that are included in these products because of specific requirements for a certain application out of the recycling process and thereby prevent negative impacts to the recycling process as such or to the quality of the recyclates.

Although the gathering of recyclables of scavengers and informal sector actors is to be seen as collection and thereby makes those recyclables available for any subsequent recycling process. As informal sector actors depend on an income from the waste fractions they collect and provide to the value chain they do not focus on LVPs.

After the collection stage waste objects will still be composed of various materials which cannot be recycled together. For example, fractions of PET drinking bottles will also contain bottle caps and labels as well as residual content from the use phase and contaminations from the collection phase.

Plastic waste sorting

Any technical process – such as also any recycling process – requires a certain quality of feedstock. Closed loop recycling requires that mono materials are processed and recycled. This can be achieved by the sorting stage.

Precise sorting is vital because different types of plastics have distinct properties that impact the recycling process as well as the quality of recyclates; improper sorting can contaminate recycling streams, reducing the quality and value of the recycled materials. Advanced sorting technologies, such as infrared spectroscopy, are enhancing the efficiency and accuracy of this process. Additionally, community involvement and education play significant roles in improving collection rates and sorting accuracy. By fostering public awareness and participation, a more reliable supply of high-quality recyclable plastics can be ensured, ultimately driving the success of recycling programs and contributing to a more sustainable circular economy.

Sorting technologies made impressive improvements in the last decades and are facilitating the recycling of plastic waste increasingly. In modern plastic sorting lines, plastic waste is typically sorted through a series of steps, including size sorting (manually or using sieves), removing foreign materials (such as metal and glass), sorting plastic materials, and finally, sizing and granulating or extruding into plastic recyclates. Foreign materials can be removed using gravity in air flow (air classifiers) or water streams (sink-float methods). Metals can be extracted by magnetic separation for ferrous metals or eddy current separation for nonferrous metals. Gravity can also separate different plastics, such as polyolefins from PET or PVC, based on density differences. This gravity sorting can be enhanced with electrostatic or magnetic fields, although the effectiveness is highly sensitive to waste contamination.

A more common method for sorting various plastics involves spreading them on a conveyor belt, identifying the plastic type using an infrared detector (e.g., near or short-wave infrared, NIR or SWIR), and then sorting it with an actuator or air jet. The standard IR detector can be replaced or supplemented by hyperspectral imaging spectroscopy (HIS) to recognize full-shape products or by an X-ray fluorescence detector to identify heavy elements such as chlorine and bromine. These advanced technologies enable the sorting of challenging materials, such as HDPE/LDPE, PET/PLA, or black products that are not identifiable with conventional NIR detectors. This sorting process results in fractions rich in films, PP, PET, HDPE, and mixed plastics (PE, PP, PS, PET). These efficient sorting technologies reportedly recover more plastic than manual household sorting and improve logistics by transporting the whole waste stream instead of individual sorted fractions [34].

Even after sorting, plastic waste often needs to be washed before it can be recycled. This cleaning process removes dirt, food residue, and other contaminants. Washing is especially important for mechanical recycling, but it can also be beneficial for chemical recycling. During the washing stage multi material fractions can be separated. Caps and labels as well as residual content and other contaminations can be removed to allow for a mono material closed loop recycling.

Plastic washing typically involves hot or cold water, along with detergents or caustic agents. It is often done after the plastic has been shredded, and sometimes combined with a process that separates plastics based on whether they float or sink in water.

However, washing plastic can be expensive. It requires specialized equipment, drying the cleaned plastic, and treating the wastewater produced during washing. Additionally, washing may not always be effective enough. For example, strong odors and certain types of contaminants might not be fully removed by traditional washing methods and might require odour removing technologies to allow for high level applications of the recyclates.

To make plastic recycling economically feasible it is key to rely on a proper plastic waste collection and sorting system. High costs make very often non-circular plastic waste treatment methods, like landfilling and incineration to the economically most attractive disposal alternative.

The plastics life cycle

Plastic pollution is a multifaceted challenge encompassing design, production, consumption, and disposal stages that must be addressed throughout the entire lifecycle of plastics. Various factors contribute to this pervasive issue, including unsustainable consumption patterns, insufficient or ineffective legislation, inefficient waste management systems, and a lack of coordination among different sectors. Additionally, the design phase often overlooks recyclability, leading to products that are difficult to process at the end of their life.

Furthermore, the production phase frequently relies on non-renewable resources and creates products with single-use applications, exacerbating the waste problem. Effective solutions require a holistic approach involving stronger regulations, improved product design for end-of-life recyclability, advancements in waste management infrastructure, and enhanced collaboration across industries and governments. Public awareness and behavioural changes are also crucial in driving a shift towards more sustainable consumption and disposal practices. Figure 22 below is illustrating the typical life cycle of plastics.

Figure 22. The plastic life cycle [35]

Plastics are typically in use for a variable amount of time before they reach the end of their useful lifetimes and are discarded. The time frame of the use-phase can range from a few days to several decades, depending on the type of plastic and its application. Single-use plastics, such as packaging, straws, and cutlery, are often discarded after just one use, typically within days or weeks.

Consumer goods, like toys, clothing, and household items, might be used for a few months to several years. Durable goods, such as automotive parts, electronics, and construction materials, can be in use for many years, sometimes even decades, before being discarded. In the building and construction sector the life cycle is the longest when compared to the other sectors. Overall, the lifespan of plastic products varies widely based on their intended use and durability [36]. This is illustrated in Figure 23 below.

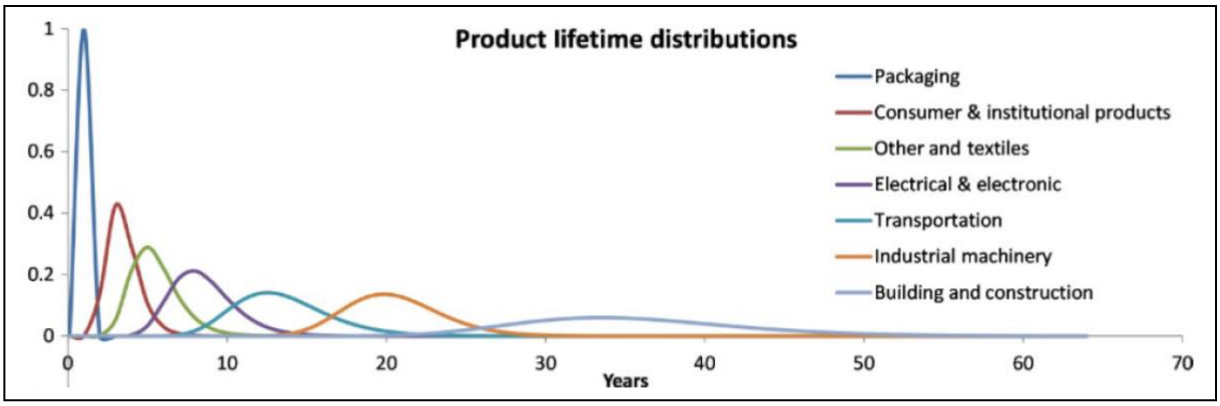


Figure 23. Product lifetime distribution of plastic products [36]

The different lifetime of plastic products has severe implications on its final management. Sectors that use plastics with short lifetimes can be regulated with an almost immediate impact, if risks related to their use, for example due to new findings of toxicity of additives, are discovered. This results in the quick phase-out of the product and the minimization of circulating pollutants through recycling.

In sectors and/or applications where plastic products remain in use for decades, it is important to consider that chemicals that might already be banned for decades – so called legacy substances – might still be contained in the products when they become waste. In those cases, chemicals / contaminant management becomes a big challenge when plastic waste is recycled.

The plastics value chain

Figure 24 displays the plastics value chain starting from crude oil down to monomers, polymers and plastics and furthermore, plastic waste at the end of the life cycle. The different plastic waste management options allow the establishment of various recycling loops that enter the plastics value chain at different stages.

On the other hand, reuse allows for value retention on the product level. Mechanical recycling methods and solutions, and precipitation-based methods aim at providing secondary polymers to the plastic value chain. Chemical recycling methods such as solvolysis based depolymerization, or liquefaction, pyrolysis and gasification aim at providing monomers or hydrocarbons for the plastics value chain. Also, incineration of plastics followed by carbon capture allow for the provision of hydrocarbons that can again be used to produce plastics.

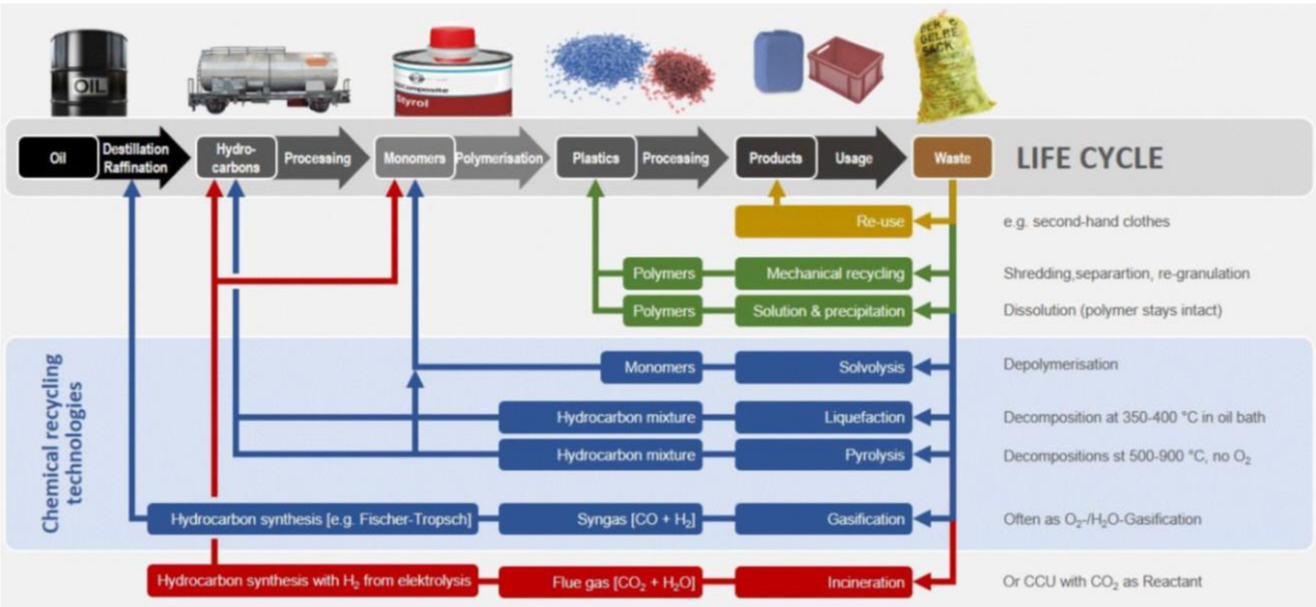


Figure 24. Value chain of plastics and recycling loops [37]

National baseline for plastic flows focusing on low value plastics

Indonesian waste management system

Waste management in Indonesia can be separated into both the formal and informal sectors. In general terms the waste management chain is composed of registered businesses and government agencies that organize the collection and transportation services, which is understood as the "formal" sector. On the other hand, the "informal" sector is made up of unregulated scrap pickers, looking for potentially recyclable material [38]. The Indonesian waste management system is shown in Figure 25.

Interestingly, according to Neo et al [38], waste recycling in the informal sector reports a higher recycling rate with almost a 100% of the recovered material being either sold to third parties or recycled, while the formal sector reports only 1% of recovery of material for recycling, with the remaining 99% being sent to final disposal, this supports the argument that the informal sector does not target the LVP as given in sections on **Low value plastics (LVP)**, and **Plastic waste collection**

It is worth noting, however, that no nation-wide formal waste management system is currently in place throughout the country [39], which can mainly be attributed to the fact that waste management falls within the scope of responsibilities of each municipality. Additionally, it is reported that the bulk of recovery relies on manual sorting and mechanical recycling, that will be used for replacing virgin plastic as an input, with a very low percentage of the material being incorporated as a raw material input for asphalt manufacturing or pyrolysis for diesel fuel.

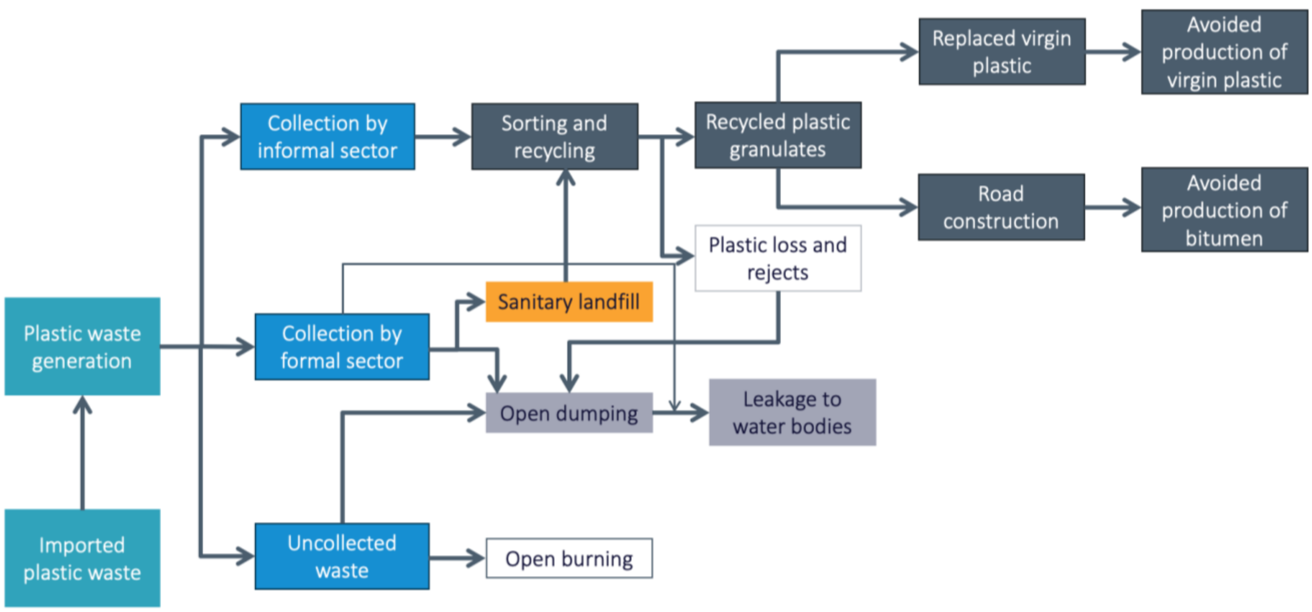


Figure 25. Indonesian waste management system [38]

Additionally, it has been reported that current formal waste management schemes dispose 100% of the collected material in sanitary landfills and open dumpsites throughout the country, this is an especially worrisome fact as plastic constitutes the second largest waste fraction of generated waste within the country [40].

According to data gathered by Zahrah et al. [40], the population in Indonesia is around 275.5 million, and municipal solid waste (MSW) generation can go up to 67 million tonnes / year. In that sense, according to data collected by the SIPSN [41], the most representative waste fraction of MSW corresponds to organic waste and/or leftovers of food with around 41.4%, followed by plastics at 19.4% as can be seen in Figure 26.

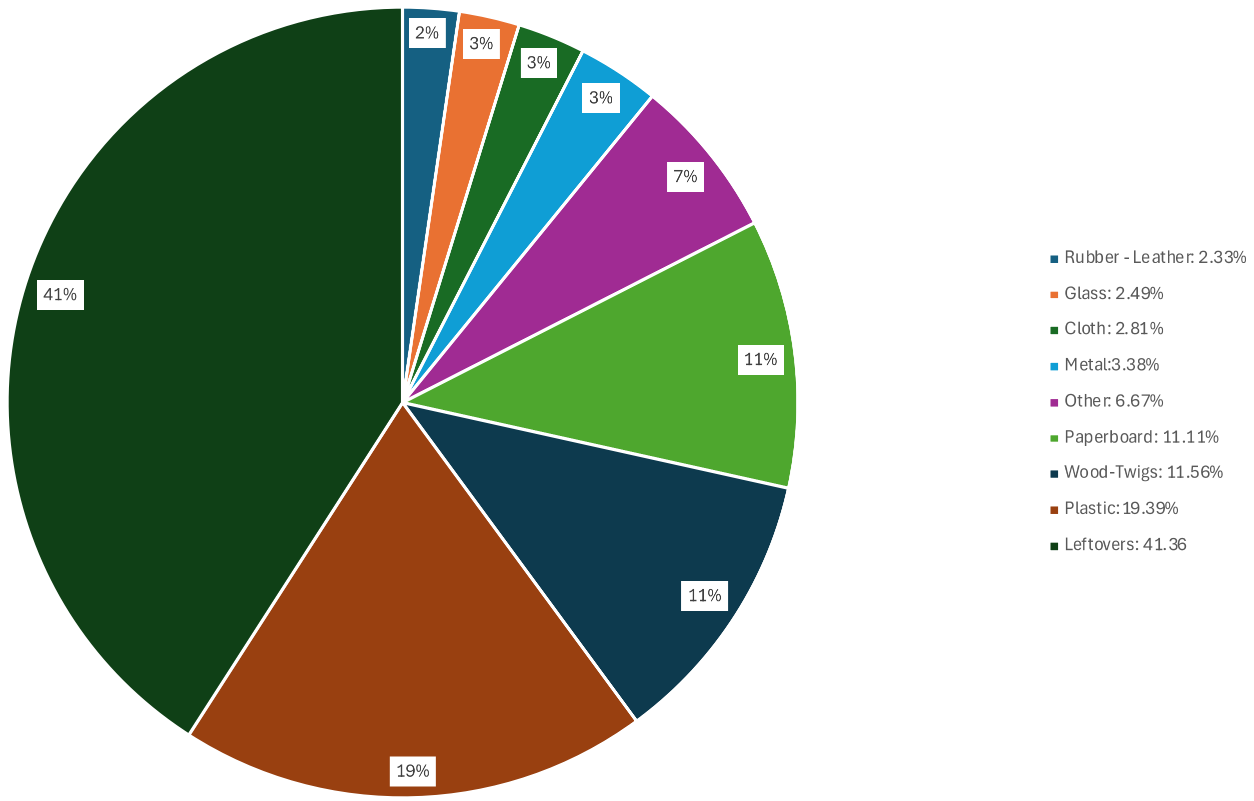


Figure 26. Representation per waste fraction (%) 2023 [41]

Furthermore, the representation of waste generation per province, detailed in Figure 27 shows that the province with the highest rate of waste generation in the country corresponds to Central Java, with a representation of 49.66%, followed by North Sulawesi with 20.78%.

On the other hand, the provinces with the lowest generation of Municipal Solid Waste (MSW) which report data to the Sistem Informasi Pengelolaan Sampah Nasional (SIPSN) Gorontalo, South Papua and Southwest Papua with 0.03%, 0.008% and 0.0018% respectively. The numbers provided are not validated since the data from SIPSN are taken from self-declaration data without further verification, therefore the quality of data depends on the commitment of each municipality to report and collect data with a proper methodology.

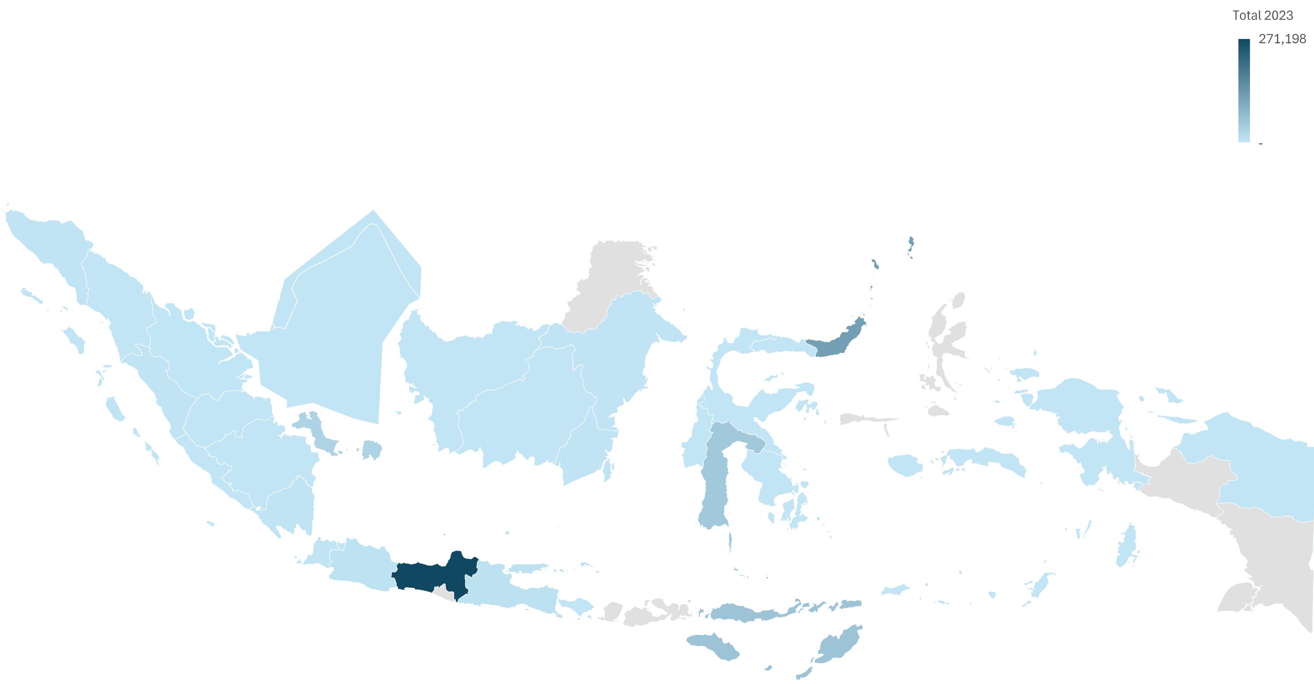


Figure 27. Municipal Solid Waste (MSW) generation per province (tonne / year) [41]

Characteristics of plastic generation and usage in Indonesia

The consumption of plastics in Indonesia is reported to be at around 17 - 23 kg/capita/year with a growth rate between 5 - 7% per year. In terms of plastic consumption based on the industrial application can be seen in Figure 28 [42].

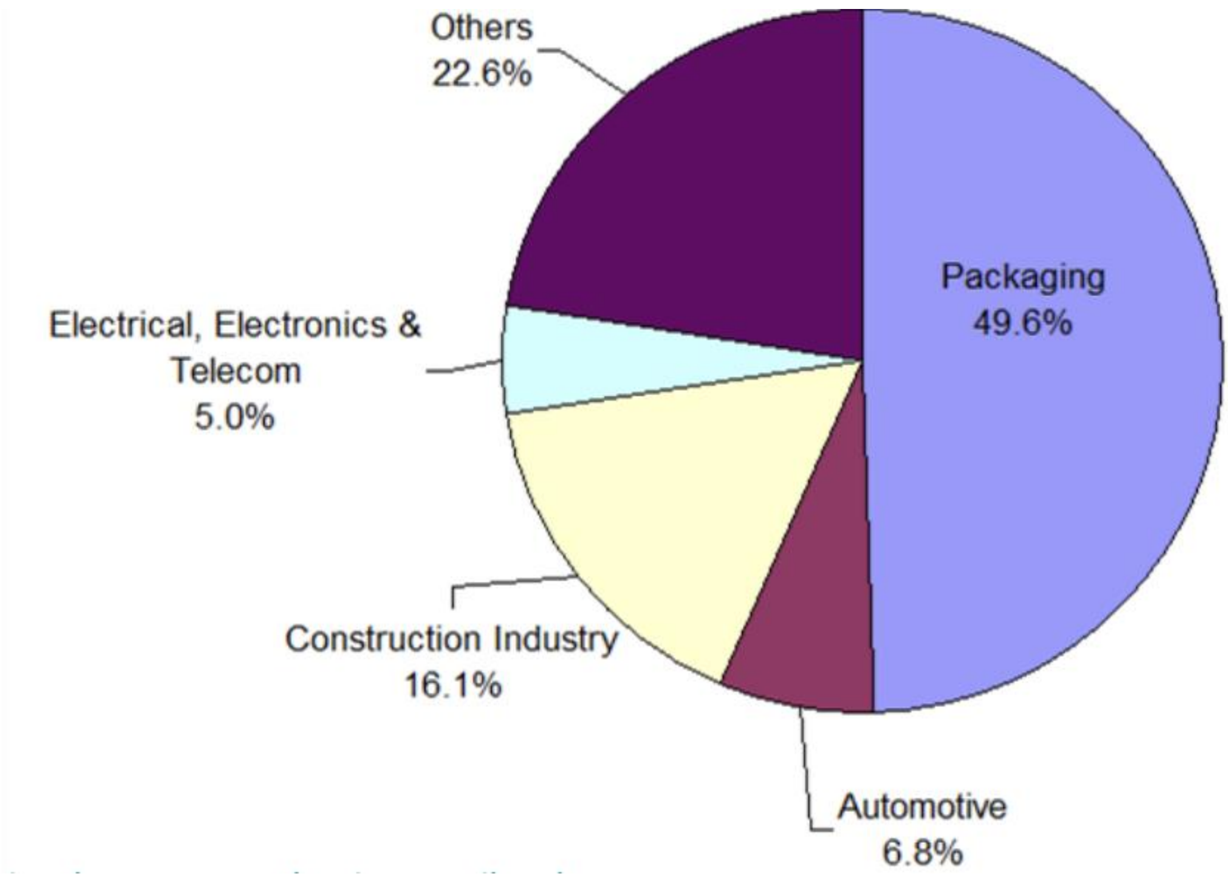


Figure 28. Plastic consumption by application in Indonesia [43].

In this sense, it is possible to identify that 49.6% of the generated plastic is used for packaging applications, while 22.6% is used for "other applications", followed by the construction industry with over 16% of consumption [42].

A more detail overview of plastic resin applications in Indonesia can be seen in Figure 29. PE accounts for 34% of plastic use and is frequently used in bags, containers, and packaging due to its strength and resilience to chemicals and moisture, its widespread use is probably due to the demand for strong, flexible packaging materials [44].

On the other hand, PP accounts for 31% of plastic use and is widely utilised in textiles, automotive parts, and packaging. Because of its robustness and adaptability, it is a well-liked option for many applications. PET accounts for 12% of plastic use and is mostly used in fibres, bottles, and containers. Its strength, clarity, and chemical resistance are what account for its widespread use; these qualities make it a useful input for the manufacturing of textiles and beverage containers [44].

PVC makes up for 11% of all plastic use and is used in window frames, vinyl records, and pipes, among other things. Because of its strength and chemical resistance, it is frequently used in industrial and construction settings. PS, which is widely used in foam packaging, insulation, and throwaway cups, accounts for 7% of all plastic use. It is a well-liked option for transient applications due to its inexpensive cost and simplicity of moulding [44].

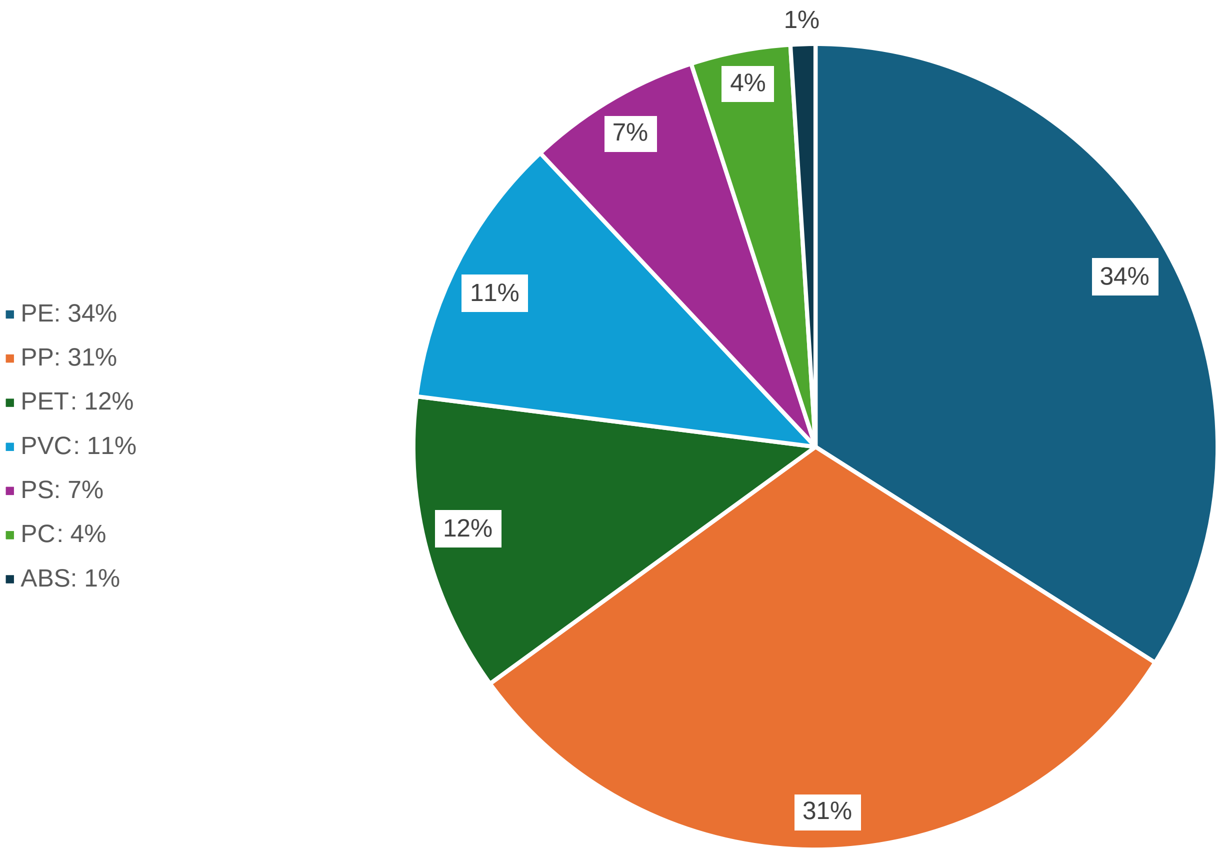


Figure 29. Consumption of plastic per type of resin [44]

PC, which is used in electronics, vehicle parts, and eyewear, accounts for 4% of plastic use. It is appropriate for applications needing strength and clarity due to its excellent impact resistance and transparency. ABS, which is frequently used in household goods, automotive components, and electrical components, accounts for less than 3% of plastic use. It is a versatile material due to its high durability and impact resistance [44].

Finally, Figure 30 shows the distribution of the national plastic industry [42]. In general terms, the country has a plastic production capacity of 2.66 MMT per year, which translates into an annual generation of plastics of 2.33 MMT, a 3.66 MMT in imported material. This flow allows the distribution into different plastic streams including household, packaging, building, finish goods, to name a few.

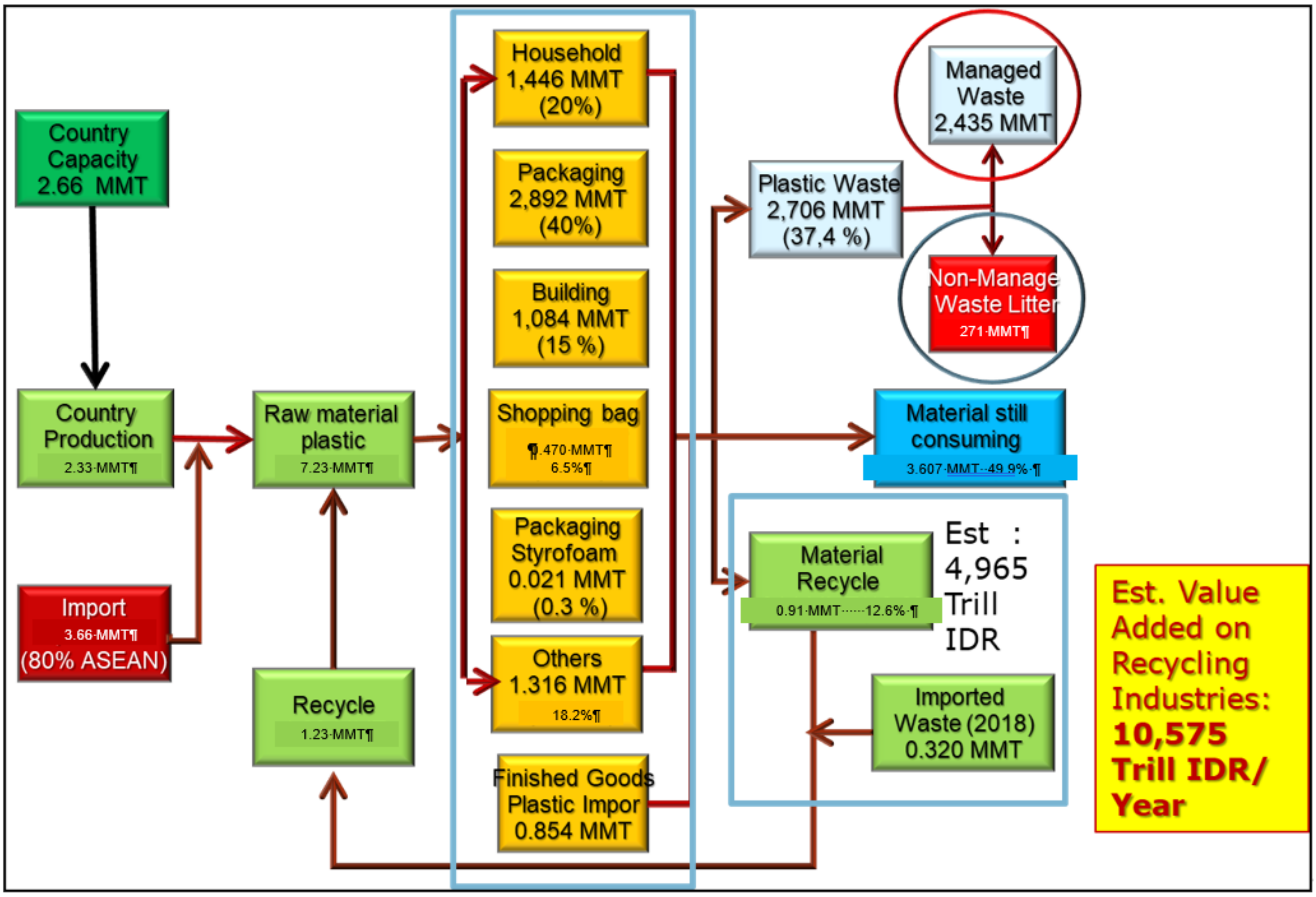


Figure 30. Plastic Industry in Indonesia [42]

Plastic waste composition at household level, landfills and marine litter

According to the representation of each waste fraction shown in Figure 26, plastic waste makes up at least 19% of the 67 million tonnes / year (12.73 million tonnes / year) of waste generated in the country. From the polymer consumption patterns detailed in the section where the **Material flow analysis and plastic waste recycling** is presented, it is possible to conclude that plastic waste generation follows a similar pattern to the one describe in the previous section of the document, with PE making up an approximate 34% of the share, followed by PP, and PET with 31% and 12%, respectively.

In terms of LVPs, an according to data form Indonesia's Ministry of Environment and Forestry, around 9.8 billion plastic bags were consumed in 2016 with a staggering 95% becoming waste, that either reached a landfill or was leaked into the marine environment [43].

A more detailed analysis per province based on data collected through waste composition surveys show that on Banyuwangi, Tabanan, and Tegal regency plastic waste composition ranges between 10.88% – 25.68% with rigid (3D) plastic representing between 4% - 9.65% and film or flexible (2D) plastic ranging from 5.87% - 18.68% [45, 46, 47].

At the same time, the study shows that plastic waste composition at household, treatment facility and landfill levels and in the same regencies is as follows:

- **At rural household level**: LDPE are 43.27%, other plastic (RIC 7) 19.27%, PET 18.71%, PP 10.49%, HDPE 5.06%, and PVC 4.58%.

- **At urban household level:** PET are 35.63%, LDPE 34.27%, other plastic (RIC 7) 10.44%, HDPE 9.78%, and PP 17.16%.
- **At recovery facilities and informal sector collection:** The results in this category are slightly different with plastic consumption at source, with PET at 13%, PP at 12%, HDPE at 11%, PVC at 8%, LDPE at 8%, other plastic (RIC 7) at 4%, and EPS at 2%.

The study also showed that in Tabanan, all plastics of high value have been diverted from the landfill, leaving only LVPs that are challenging to recover due to the presence of mixed plastics. The composition of plastic waste in Indonesia is as shown in Figure 31 [48], with food packaging (57%) making up the majority of generated waste, followed by plastic bottles (13%) and plastics and carboards (8%) [48].

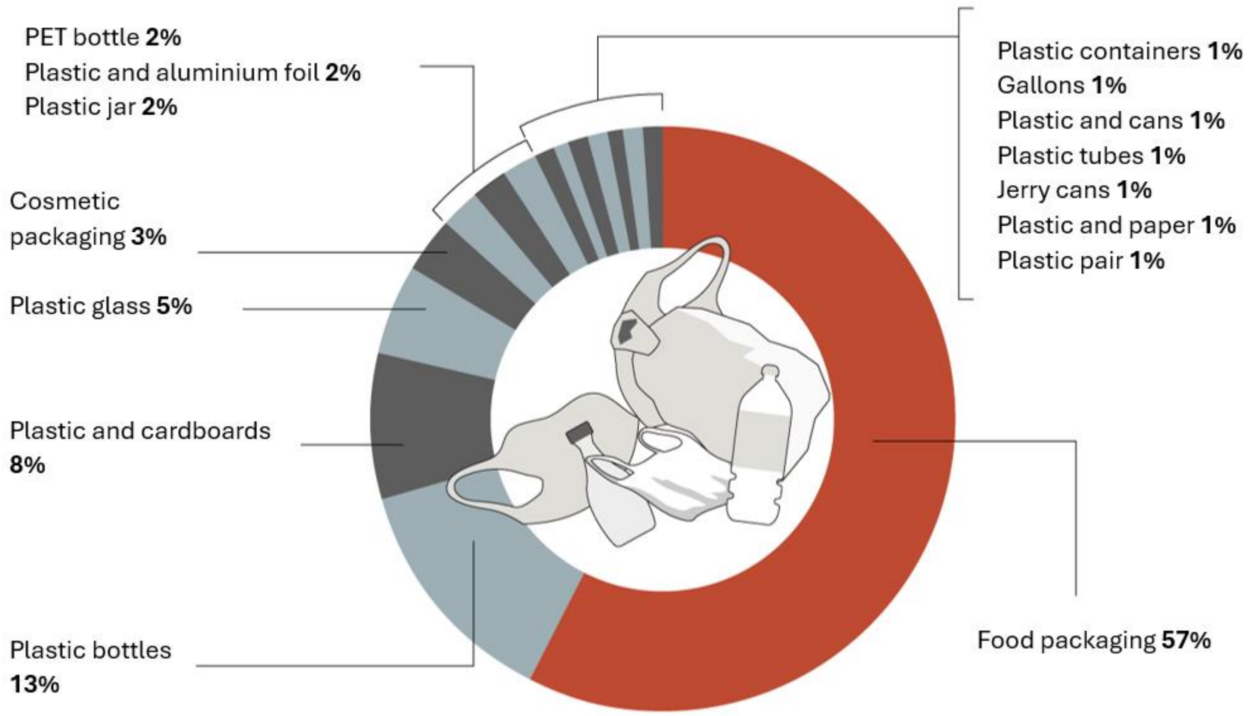


Figure 31. Indonesia's plastic waste composition [48]

Paying closer attention to the resins that end-up being disposed of in the Marine Debris Hotspot Rapid Assessment Report carried out by the Word Bank Group in 2018, concluded that around 16% of all waste found in marine water ways or leaked into the environment belong to the PE resin or high-density PE, 9% of other plastic material, 5% from plastic packaging, and 1% from plastic bottles as can be seen in Figure 32.

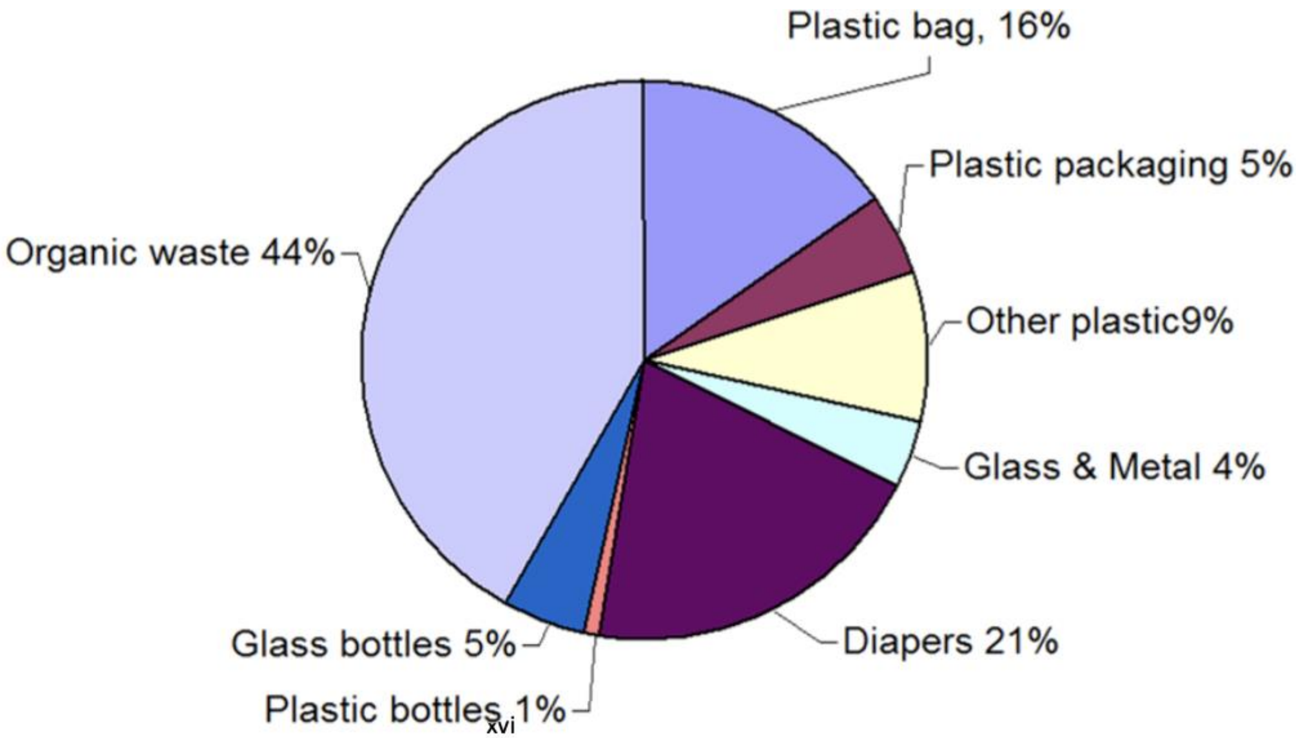


Figure 32. Marine litter composition [43]

The first stranded macro-debris study carried out on a national scale in Indonesia analysed data from 18 beaches from February 2018 until December 2019. Results of the study show that the highest amount of stranded macro debris was found in Ambon, Manado, Takalar, and Padang.

Plastic (46.38 %) was the most prevalent type of debris across all macro debris categories, with single-use plastics such as plastic sachets, plastic bags, and plastic bottles being the dominant macro-plastic debris (64.64 %).

Plastic sachets/multilayers were the most abundant material accounting for 12.15 %, followed by thin plastic wrap/bags (11.96 %), plastic bottles (11.42 %), straw, cotton buds, pieces (8.05 %), plastic cup (7.64 %), Styrofoam packaging (6.99 %), thick plastic wrap, sack (6.81 %), cigarettes filter butts (6.47 %), rope, fishing line, fishing rod, plastic rope/small net pieces (4.78 %) and shoes, sandals, gloves (3.15 %).

The most intriguing result is that the high value plastic more likely to be found in places where distance from Java Island increases. This shows that centralized plastic recycling industries bring inequality of recycling rate of high value plastic around Indonesia [49]. It is estimated that an approximate of 62,000 tonnes of plastic entered Indonesian waters between 2018 and 2019.

Material flow analysis and plastic waste recycling

Indonesia's plastic recycling industry processes about 1.1 million tonnes annually, short of its 2 million tonnes capacity due to insufficient segregated waste. Only 10% of plastic waste was recycled in 2019, primarily rigid plastics such as PET, HDPE, LDPE, and PP [50]. Flexible plastics are often openly dumped or openly burned due to the prevailing boundary conditions with regards to the legislator and economic framework.

In NPAP Report [51] the fate of plastic waste is discussed depending on archetypes, such as megacities (population is >1 million inhabitants with population density >2,500 inhabitants / km^2), medium cities (population density >1,500 inhabitants / km^2), rural (adjacent to archetype 1 and 2), and remote cities (not properly connected to larger cities).

Waste-generation volumes per person are highest in wealthier archetypes, average plastic waste-collection rates are dramatically higher in mega-cities: 74% compared to 20% and 16% in rural and remote city areas respectively, informal sector workers (waste pickers and aggregators) are most active in and around large cities, as this is where recycling plants are concentrated, and population density is highest.

Most plastics are not collected into a managed waste system after use (4.2 million tonnes, or 61% of plastic waste). This leaves households and small businesses with no other option than to dispose of them in an environmentally harmful way: 78% of uncollected plastic waste is burned by households, often close to homes, 12% of it is discarded into bodies of water and 10% is dumped on land or buried and can then end up in bodies of water through rainwater runoffs. Much larger volumes are burned by households, often close to homes (about 78% of uncollected plastic waste). 72% of mismanaged plastic waste comes from medium cities and the rural archetypes, 64% of mismanaged plastic waste comes from Java, which is the most populous island (56% of Indonesians live in Java) [51]. Overall end of life plastic waste fate can be seen in Figure 33.

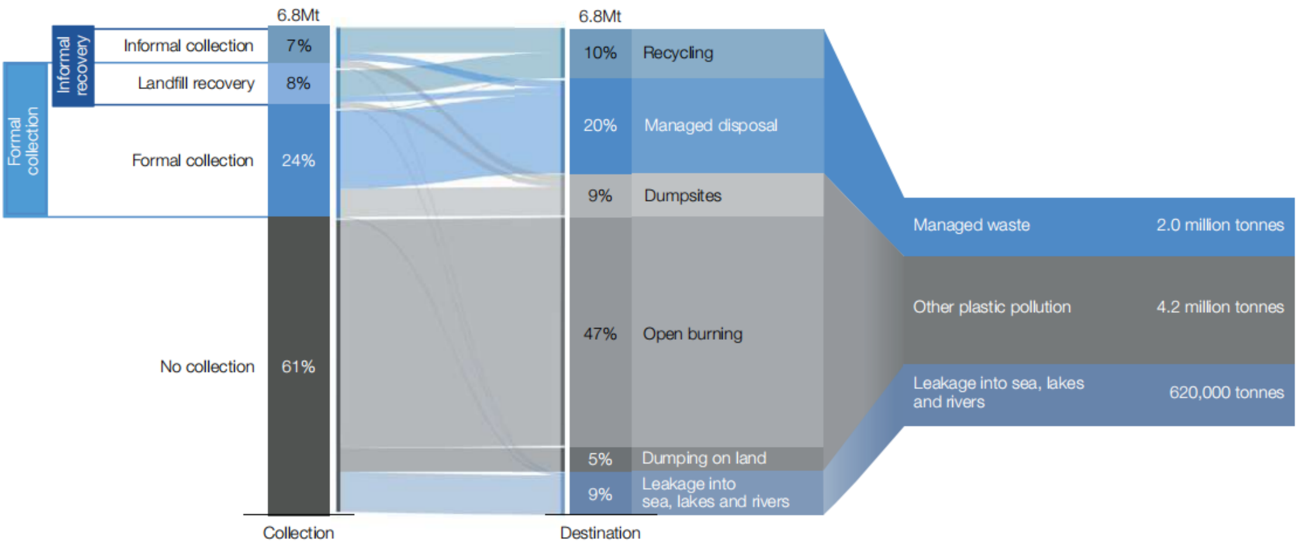


Figure 33. Plastic Waste End of Life [51]

Plastic waste in Indonesia often lacks proper segregation after use, leading to increased impurities that fail to meet industry standards, this makes it challenging for manufacturers to produce recycled plastic comparable to virgin resin. Imported plastic scrap dominates recycling feedstock due to its higher quality compared to domestic post-consumer plastics and arises after China National Sword Policies was enacted and creates a diversion from the China plastic recycling industries to South-East Asian countries, like Malaysia, Indonesia, and Vietnam. Improving the quality of domestic post-consumer plastics is crucial to expanding recycling opportunities. Additionally, public perception remains a barrier, with recycled plastic products viewed unfavourably for their perceived lower quality compared to virgin plastic alternatives, hindering growth in Indonesia's recycling industry [52].

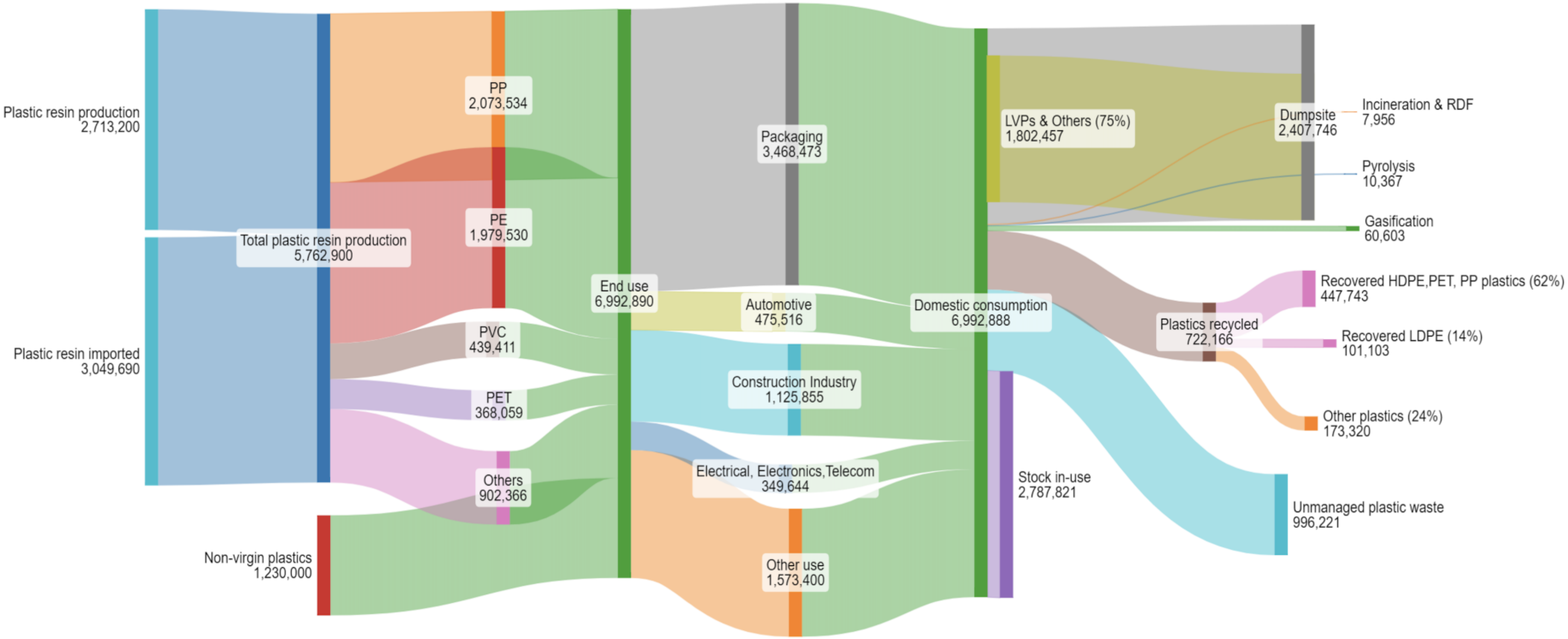


Figure 34. Plastic mass flow balance in Indonesia (Tonnes/annum)

Plastic waste recycling in Indonesia formally relies on Regulation No. 13 / 2020 of the Ministry of Environment and Forestry (MoEF), through which the concept of a waste bank is defined as "*a place for sorting and collecting waste that can be recycled and / or reused that has economic value*" [53], as well as Regulation 13 of 2012 on the *"guidelines for the implementation of Reduce, Reuse and Recycle through Waste Banks".* MoEF also issued Regulation No. 75/ 2019 for EPR implementation roadmap to increase its recycling rate by expanding source of funding by implementing an EPR scheme [52]. EPR implementation still voluntary and implemented for three sectors, i.e. food, consumer goods, and personal care industries, modern retail, hotel and restaurant.

Overall, the concept of a waste bank was proposed as a decentralised waste management strategy for separation at source for recyclables. Waste bank divided into two types depending on capacity and the subscriber. Type one is waste bank unit or WBU, which most of the activity on outreach and trade of recyclables are happening and, the second one is central waste bank (WBC), which operates to cater WBU as collection aggregator, a more business-oriented paradigm [40].

According to statistical information reported for 2020, the province with the highest number of waste banks per province can be found in East Java, with over 2,941 WB, and the lowest corresponding to the Banten province with 252 WB [54]. However, performance of waste bank to collect recyclable often very low compared to total waste generation, in Banyuwangi, Tabanan and Tegal Regencies, waste bank divert recyclables from landfill are 0.03%, 1.24%, 0.23%.

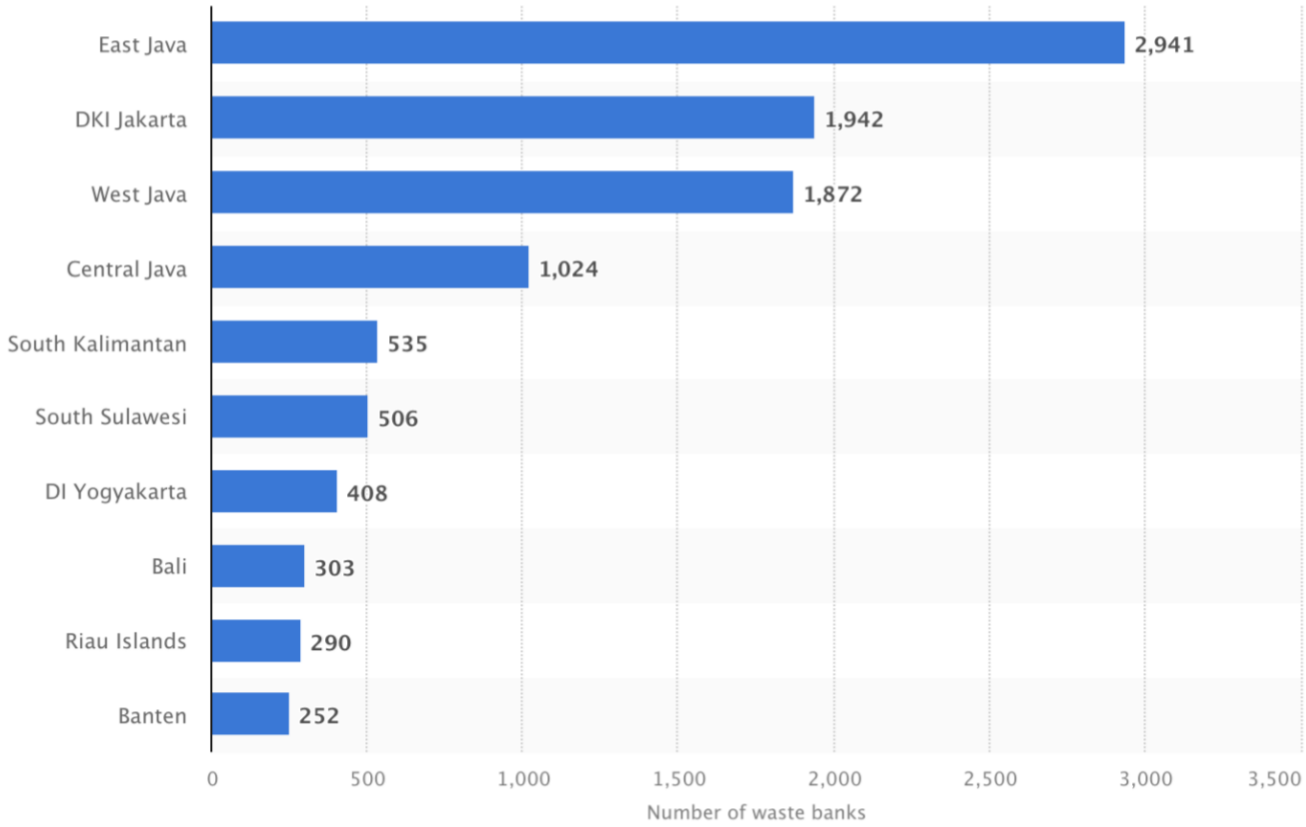


Figure 35. Number of waste banks per province – Indonesia [54]

The Informal Recycling Sector (IRS) also plays a crucial role on plastic recycling activities in Indonesia. These activities related to several actors from intermediate waste buyers and waste pickers as upstream layer of the plastic value chain, chain of junkshop and scrap dealer as midstream layer of the plastic value chain, to recycling factory as a downstream layer of the plastic value chain. Their contribution estimated up to 12 % from total recycling activities [55], whilst from Banyuwangi, Tabanan, and Tegal are 3.44%, 17.37%, and 1.26% [45, 46, 47].

The top 5 plastic material collected by IRS are shown in Figure 36.

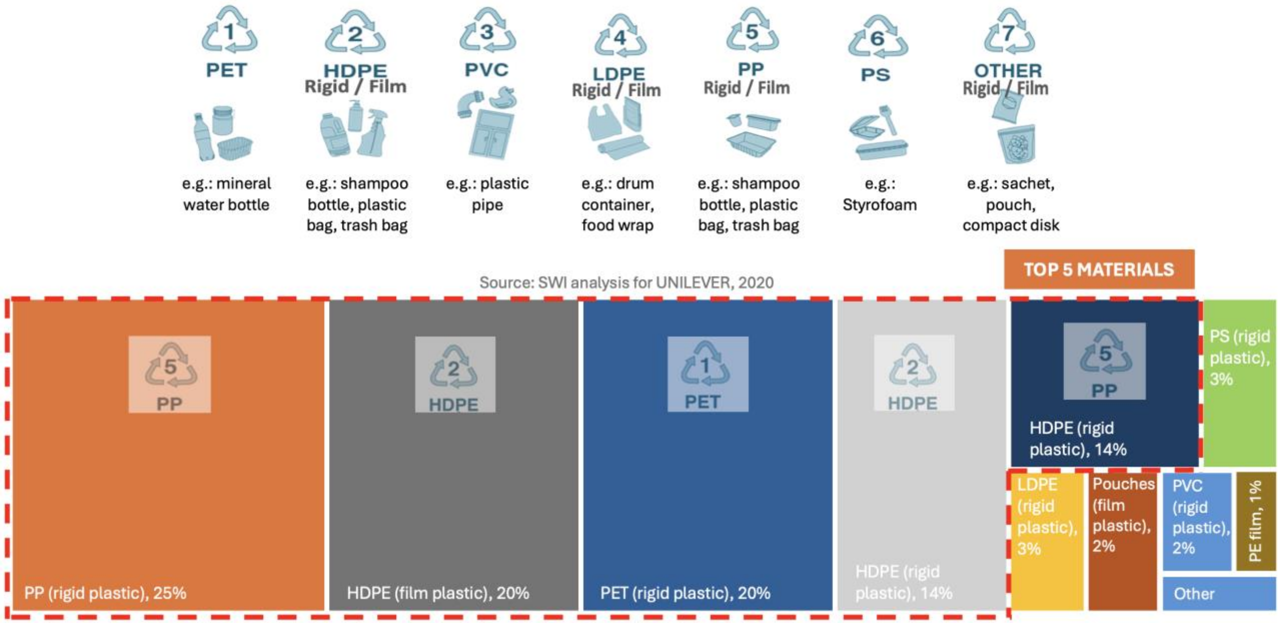


Figure 36. Plastic material collected by IRS [45, 46, 47]

Downstream plastic value chain

Plastic value chain in Indonesia is mainly stationed in Java Island as the most populous island. [51]. There are 189,348 tonnes of plastic waste generated per month in Java. Figure 37 illustrates the gaps in the waste management system by showing that a significant amount of plastic waste still ends up in landfills or the environment and how much is recycled.

A staggering 88% of plastic waste is either landfilled or scattered in the environment, with only 11.38% being collected. Of this collected waste, 82.6% is gathered by waste pickers from the IRS, 8.7% is directed to reuse, reduce, and recycle waste management sites, 6.5% goes to integrated processing facilities, and 2.2% is processed through waste bank units. In the midstream level, waste collectors manage 98% of the collected waste, leaving just 2% in the main waste bank. From upstream to midstream level, there is a reduction of approximately

1,000 tonnes per month in waste, which reflects the portion of residual of plastic waste recycling activities. Finally, in the downstream level, 75% of the plastic waste from the midstream process is handled by recyclers, while the remaining portion comes from islands outside of Java.

The remaining portion remains unprocessed due to the waste management systems already operating at full capacity. On a national level, the gap on plastic waste recycling activities with its generation and capacity are shown in Figure 38.

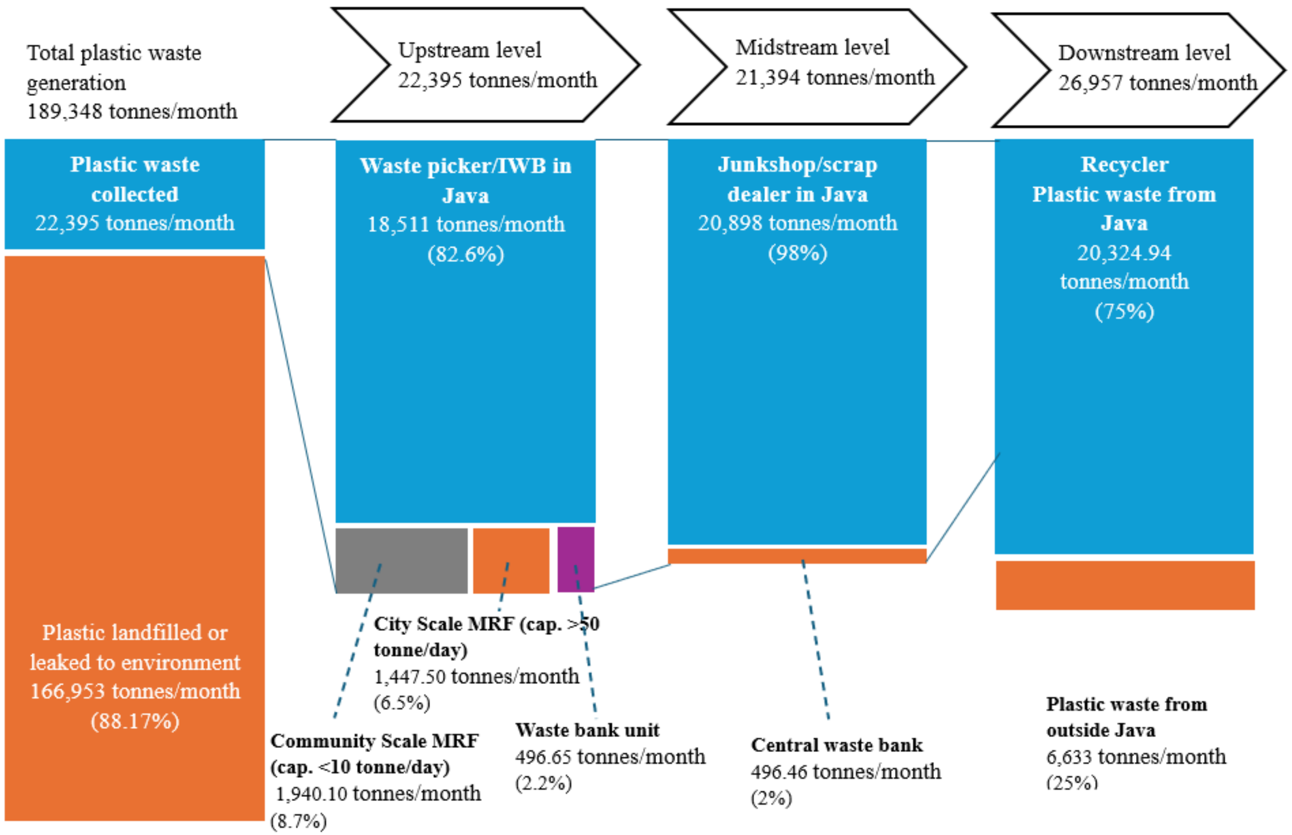


Figure 37. Plastic waste material flow in Java [50]

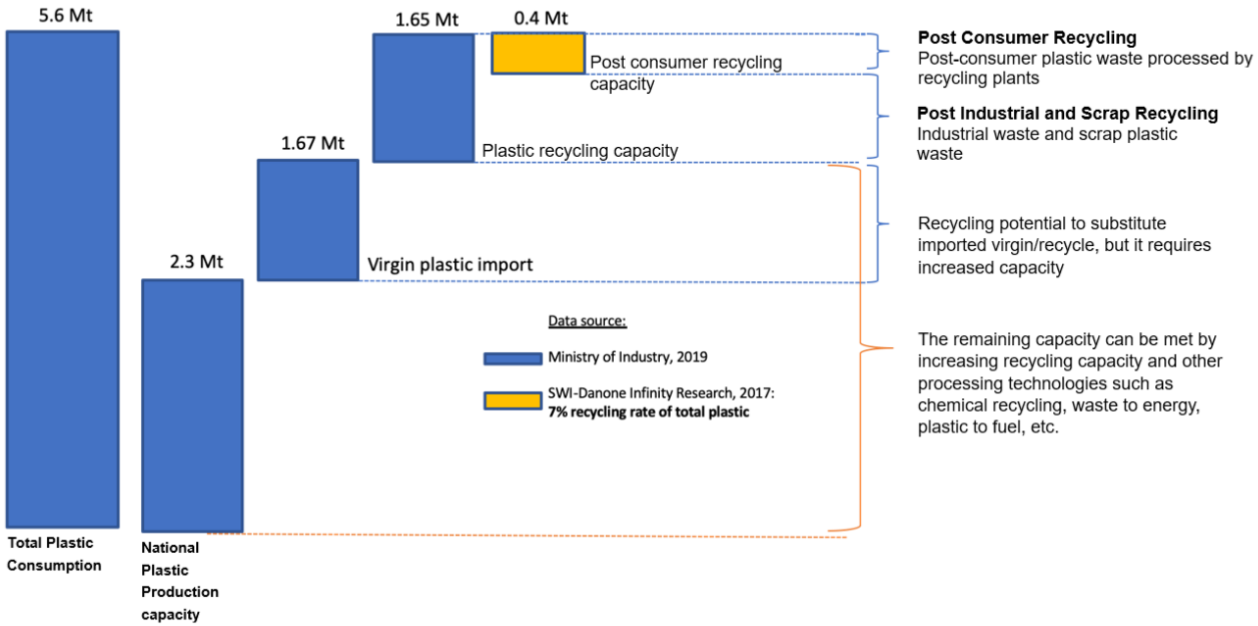


Figure 38. Plastic waste recycling gap [50]

Plastic waste hotspot

Figure 39 depicts the severity of mismanaged waste in each Indonesian province. The term "mismanaged waste" is more general and refers to any improperly managed garbage. It covers both inadequately managed waste and waste that is not collected. Not only can improper waste management result in leaks into the environment, but it can also take the form of open burning, dumping, and littering.

Waste leakage patterns are often linked to the socio-economic status of an area: poorer neighbourhoods have limited access to public infrastructure and services, they typically experience inadequate waste management systems and therefore would generate significant waste leakage. As previously stated, most waste management services are handled at a local level, with the municipalities being the primary entity responsible for the provision of the service [56].

This situation allows for communities within more difficult-to-reach-areas to dispose of their generated waste in communal containers that turn into waste leakage hotspots [56]. However, despite these efforts, it was shown that there was a continuous absence of local leadership, monitoring systems, and law enforcement to stop illegal burning and dumping.

When it comes to waste management in both tidal and non-tidal locations where hotspots have been identified, the public is typically not provided with adequate or consistent information. There is a lack of knowledge regarding recycling and the existence and function of waste banks in both tidal and non-tidal environments. Behaviour relating to waste disposal is still alarmingly limited in knowledge [56].

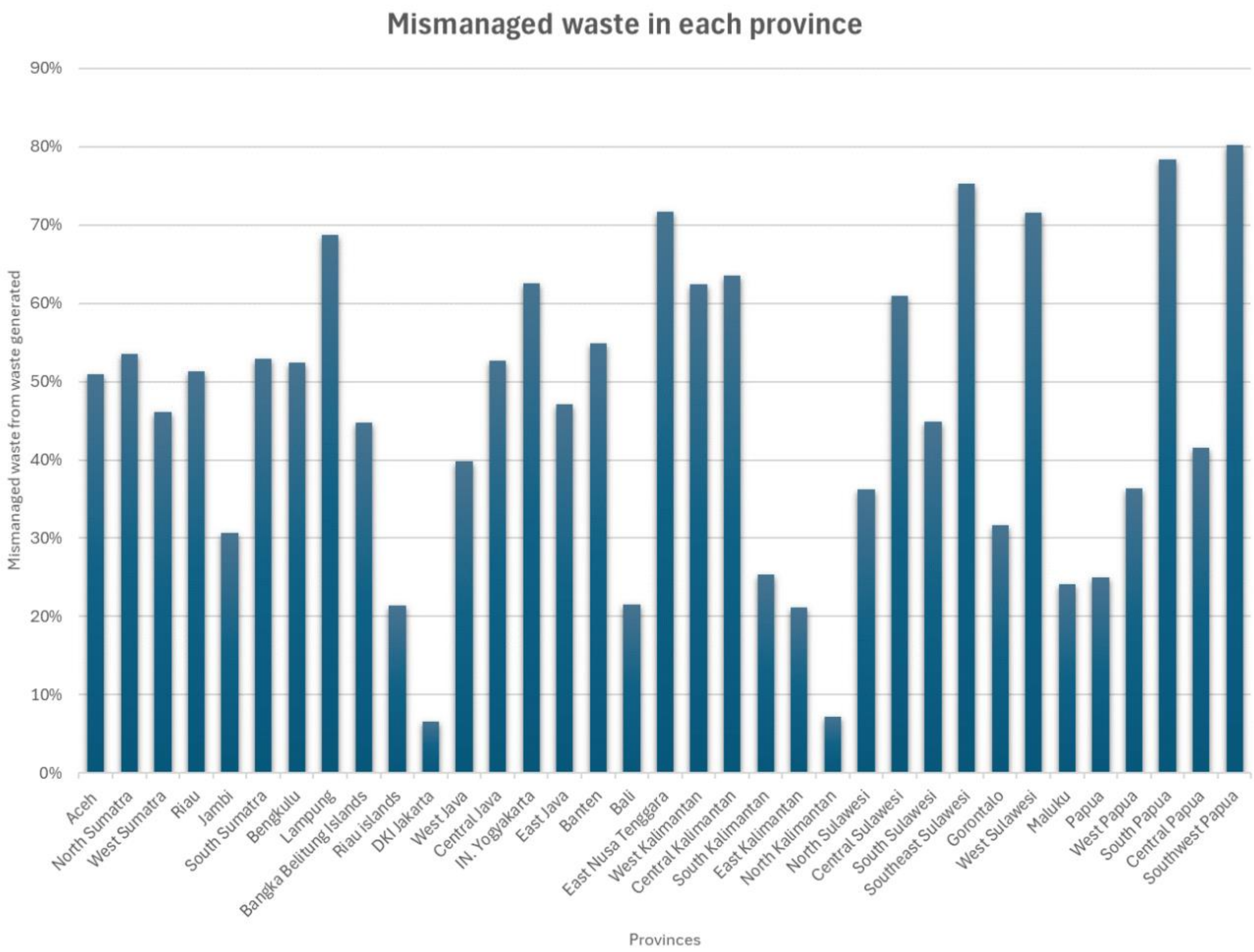


Figure 39. Mismanaged waste per province [41]

From, mismanaged low value plastic waste estimated from the composition data of waste from each region is as follows. Java island has the highest amount of mismanaged plastic waste, with West Java at 61,377 tonnes per year, Central Java at 85,915 tonnes per year, and

East Java at 63,107 tonnes per year. These provinces are densely populated and industrially developed, contributing to higher waste generation. Furthermore, as seen in Figure 37, 6,632.06 tonnes per month of plastic waste is transported from other islands into Java, adding into its abundance. Meanwhile, data for North Kalimantan, West Sulawesi, and Central Papua were impossible to process as there were no waste composition data.

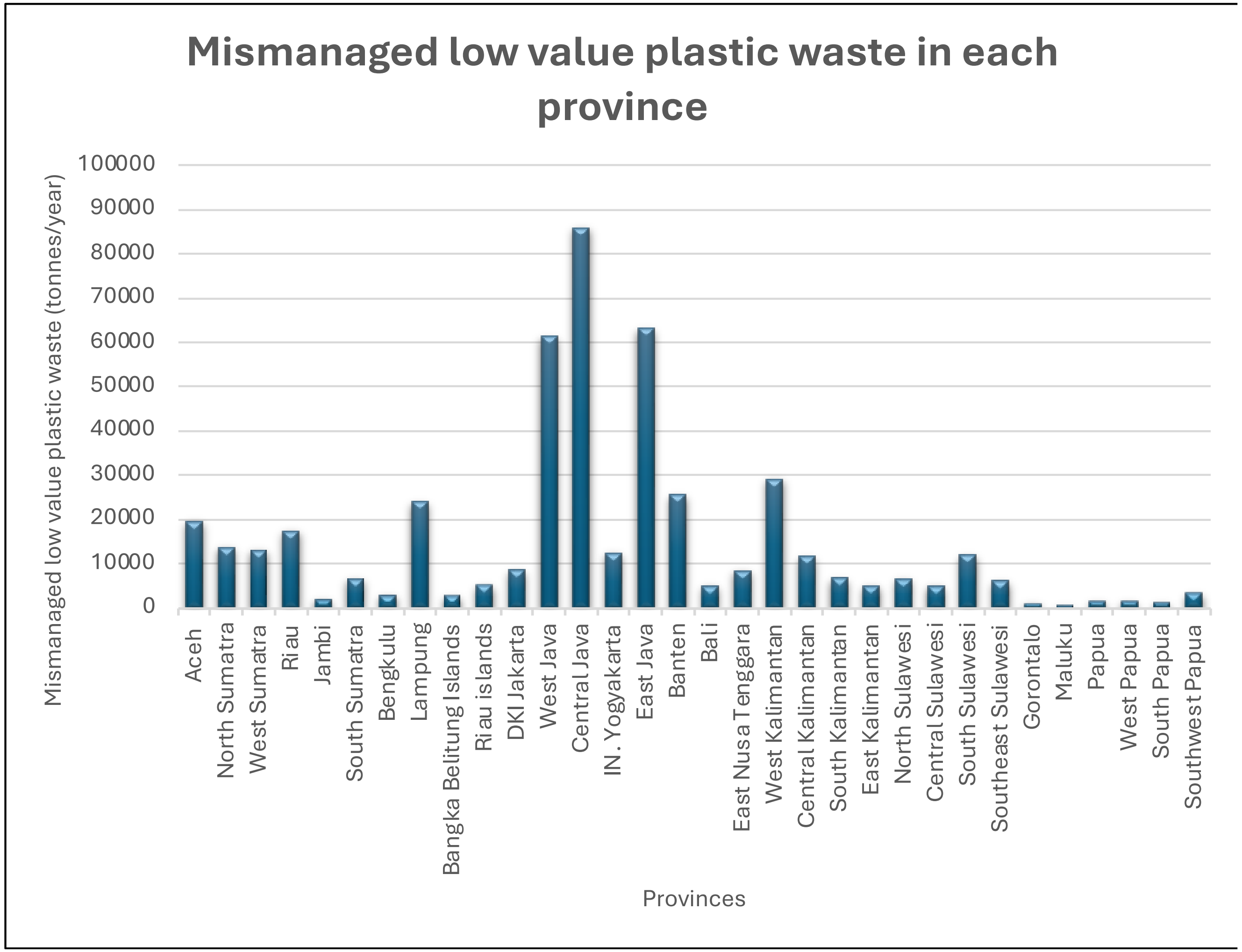


Figure 40. Estimation of mismanaged low value plastic waste per province in Indonesia [41]

Analysis of challenges and limitations in recycling low value plastic waste

The term low-value plastic suggests that this material stream contains plastic of lower quality as compared to other plastic waste streams that contain better quality of plastic. This is not correct; the term rather refers to the fact that based on the properties and nature of that plastic waste material stream it is more difficult to obtain revenues on the recycling markets and due to higher costs per tonne for the logistics and recycling it is economically less interesting to deal with that material stream. From a pure material handling perspective, it is suggested to differentiate between a 2D (2-dimensional, flexible or film) fraction and a 3D (3-dimensional, rigid) plastic waste fraction with a higher mass to volume ratio.

The challenges and limitations regarding low value plastic waste recycling are on one side related to the material stream and its properties and specialities and on the other side are related to the plastic recycling market and state of the waste management sector in a specific region. These aspects will be discussed in the following chapter.

Market related challenges and limitations

State of evolution of the plastics recycling market

The global plastic recycling market is experiencing significant growth, projected to increase from approximately $51.7 billion in 2023 to $96.48 billion by 2031, with a compound annual growth rate (CAGR) of 9.5% during this period [57]. However, the market faces challenges, primarily due to the low price of virgin plastics, which diminishes the economic incentive for recycling. Right now, recycled plastic is 35% more expensive than virgin plastic [58] ; this has resulted in a lack of focus on material recycling, especially for low-value plastics such as multilayer packaging and sachets, which are difficult to recycle due to their complex compositions and low economic value.

There is a shortage of recycled plastic supply, with an estimated 6 million tonnes shortfall per year [59]. While recycled plastic has the potential to be cost-competitive with virgin plastic, the current higher costs of recycling, quality issues, low oil prices, and supply-demand dynamics make recycled plastic today more expensive in most cases. Nevertheless, due to CSR commitments as well as legally binding stipulations regarding recyclates content in products the demand for recyclates is growing fast.

Plastic recycling technologies have evolved over the years, including both material and chemical recycling methods. Mechanical recycling – a subset of material recycling -, which involves sorting, cleaning, and reprocessing plastics, remains the most common approach. Chemical recycling, which breaks down plastics for example into their monomers for repolymerization, is gaining traction as it can handle a broader range of plastics, including those that are traditionally difficult to recycle. Historically, the recycling of plastics was primarily focused on a limited number of materials. However, advancements in recycling technologies and increasing environmental awareness have led to a broader range of plastic types being recycled. Currently, the most recycled plastics include [60, 61]:

- Polyethylene Terephthalate - PET is the most widely recycled plastic globally, with recycling rates exceeding 50% in some regions like Europe and South Korea. PET is typically recycled through mechanical processes where it is cleaned, shredded, and reprocessed into flakes or pellets. Innovations also allow PET to be recycled back into new bottles or transformed into fibres for textiles.
- High-Density Polyethylene: HDPE is accepted at most recycling centres. It is often downcycled (a recycling practice that involves materials being reused for lower-value products). Like PET, HDPE is mechanically recycled. It can be reprocessed into various products, including plastic lumber, piping, and containers.
- Polypropylene: PP is increasingly being recycled, though it is less common than PET and HDPE. Its recycling rate is growing due to increased consumer awareness and demand for sustainable products. PP is primarily recycled mechanically, but advancements in chemical recycling are also being explored to handle contaminated streams.
- Polyvinyl Chloride: PVC recycling is more specialized and often limited to certain applications like piping. Its recycling rate is lower compared to PET and HDPE. PVC can be recycled mechanically, but contamination issues make it challenging. Advanced technologies are needed to improve the recycling process.
- Polystyrene: PS is notoriously difficult to recycle, with low recycling rates. It is often found in disposable cutlery and packaging materials. Mechanical recycling is possible, but the process is not widely adopted due to contamination and economic viability concerns.
- Low-Density Polyethylene: LDPE is often excluded from curbside recycling programs, but there is a growing interest in its recycling. Specialized facilities can recycle LDPE, but the process is less common and often involves mechanical recycling.

- Flexible Plastics: Flexible plastics, such as films and bags, are challenging to recycle due to their lightweight nature and tendency to clog machinery. New sorting technologies and chemical recycling methods are being explored to improve the recycling rates of flexible plastics.

The plastic recycling industry in Indonesia predominantly focuses on high-value plastics, particularly PET. Indonesia's plastics market size was valued at $8.63 billion in 2022 and is likely to reach $14.58 billion by 2031, expanding at a compounded annual growth rate (CAGR) of 6% [62].

The packaging sector remains the major application of plastics in Indonesia, with the packaging market size poised to register a CAGR of more than 3% during 2022-2027. This focus is largely due to PET's higher economic returns than low-value plastics, which remain underrepresented in the recycling efforts. The country's recycling infrastructure and market dynamics reflect a broader trend where high-value materials receive more attention, leaving low-value plastics largely unaddressed.

The underrepresentation of low-value plastics in Indonesia's recycling efforts poses significant environmental challenges, as these materials contribute substantially to plastic waste. The lack of adequate recycling solutions for multilayer packaging and sachets exacerbates waste management issues and limits the potential for economic benefits that could arise from a more comprehensive recycling strategy.

Incentives for recycling

While many governments have introduced subsidies and financial incentives to promote recycling, their effectiveness varies significantly. In many cases, these incentives are not sufficient to cover the high costs associated with recycling processes, such as collection, sorting, and processing. For instance, the investment required to build comprehensive waste management systems in emerging economies is substantial, estimated to be between $560 billion to $680 billion over ten years, which far exceeds available subsidies and financial support [63]. Popular mechanisms like Extended Producer Responsibility (EPR) schemes, which require producers to finance the collection and recycling of their products, are difficult to implement effectively in emerging economies without clear guidelines and support.

Plastic credits have been one solution to tackle the LVP issue, as they are seeking to fund the operational cost to collect and use the kind of plastic in cement kilns, however these are voluntary and not bind by any regulatory compliance globally.

This complexity deters companies from engaging in recycling initiatives, limiting the overall impact of financial incentives. The recycling initiatives for low-value plastics rely heavily on government funding and subsidies, which can be unstable or subject to political changes or shift of the financial flows. This dependence leads to program availability and effectiveness fluctuations, making long-term planning difficult for businesses and recycling facilities.

Furthermore, there is a legitimate cause for concern on the part of manufacturers. Mechanically recycled polymers can have reduced chemical, thermal, and impact resistance when compared to their virgin counterparts. This naturally causes brands and manufacturers to hesitate when introducing any new product with sub-par quality compared to previous goods sold.

Currently, Indonesia's plastic recycling rate is around 7%, focusing on high-value plastics like PET bottles, which have a recycling rate of nearly 100% [64]. Due to their complex composition and low economic value, low-value plastics such as multilayer packaging and sachets need to be more represented in recycling efforts. While the government has introduced EPR regulations to hold producers accountable for packaging recycling, implementation still needs improvement. Despite these challenges, Indonesia is beginning to embrace a circular economy approach, with the government targeting recycling to 30% by 2025 [65].

Costs of logistics and recycling

The cost of logistics has an impact on the recycling efficiency of LVPs. There is a high collection and transportation costs associated with it, as LVPs have a low mass-to-volume ratio, meaning they are bulky relative to their weight. The low density of these materials requires more trucks and fuel to transport the same amount of plastic, driving up logistics costs significantly. This makes them expensive to collect and transport compared to their value [66]. Further, the dispersed nature of LVP waste generation leads to high collection costs. Small items are often too lightweight to be efficiently collected. Thus, also making supply of feedstock for recycling inconsistent.

Insufficient collection systems lead to the widespread littering and open burning of low-value plastics, contributing to environmental pollution and public health risks. In Indonesia, waste collection services are often limited or non-existent in rural and peri-urban areas, leading to the improper disposal of low-value plastics. The prevalence of littering and open burning in these regions contributes to air pollution, soil contamination, and the degradation of ecosystems.

Even when the waste is collected, the current sorting processes are labour-intensive, requiring manual separation of different plastic types, adding costs to the recycling process as discussed in section **On the importance of collection and sorting.** For collected LVPs, contamination issues further increase costs, as impurities must be removed to maintain the quality of recycled materials. If it is mixed plastics, then they have varying chemistry and melting points. If not adequately sorted, materials can contaminate the recycling stream and reduce the quality of the recycled plastic. The high collection, sorting, transportation and processing costs are passed on to recycled plastic, making it less attractive to manufacturers.

Additionally, global trade dynamics have affected Indonesia's recycling landscape. With restrictions on plastic waste exports, particularly following China's National Sword policy, Indonesia has become a destination for low-value plastics from developed countries [67]. This influx of non-recyclable waste adds to the burden on local recycling systems, exacerbating the challenges further.

Further, revenue potential for most low value plastic is limited, as if made to raw material, they compete with cheaper virgin material options, and if made into any new product or composite for alternative use, the margins are low and there is barrier in acceptance of the product for commercial use.

Material stream-related challenges and limitations

Contamination is a problem as it reduces the recyclability of low-value plastics. These materials often have high grit, grease, and residual content, which can contaminate the entire recycling stream if not properly removed [68]. In Indonesia, MSW also contains a substantial proportion of low-value plastics, which are commonly contaminated with food residues, making them difficult to recycle [69]. Cultural practices and social norms in Indonesia, such as using plastic bags for wet waste disposal, contribute to the contamination problem.

Low-value plastics are often used in composite materials, such as multilayer packaging, which combine different plastic types and non-plastic materials. These composites pose a challenge for recycling, as they are typically designed for functionality rather than recyclability. The lack of focus on design for recycling and the impossibility of manually sorting or mechanically separating these materials lead to negative quality implications on the recyclate. In Indonesia, comprehensive data on the flow of plastic composite material streams is lacking, making it difficult to quantify the scale of the challenge. However, the country's widespread use of multilayer packaging and sachets suggests that composite materials contribute significantly to the low-value plastic stream.

Data gaps

authorities do not have comprehensive data on the waste generated by their populations, which hinders effective policymaking and planning. Waste generation estimates are often outdated, sometimes exceeding a decade old, leading to a reliance on incomplete or inaccurate information. This inconsistency sharpens the challenge of developing appropriate strategies for managing plastic waste as authorities struggle to understand the scale and composition of the waste they are dealing with.

Indonesia generates a significant amount of plastic waste, yet comprehensive data on the types, quantities, and sources of this waste is lacking. This absence of readily available baseline data complicates efforts to develop effective recycling strategies and waste management policies. The same is also reflected in baseline presented in this report, where data availability from government statistics is not there and had to be gathered from multiple sources with proxies, which must be normalised to estimate the waste flow. Though, Indonesia is third largest contributors to ocean plastic pollution [70], the specific contributions of low-value plastics and their contamination sources are not well-documented.

Technological challenges and limitations

One of the primary technological challenges is the incompatibility of different plastic types. Many low-value plastics are composites or multi-materials, making them difficult to sort and recycle effectively. Current mechanical recycling processes struggle to handle these mixed plastics, leading to contamination and reduced quality of the recyclate, and there is no mechanical recycling option for the composite plastic waste that can produce recycled material that replaces the dependency on virgin plastic. When we look at broad range of chemical recycling, there are very few commercial options, which again are conditional to the purity of input plastics and are capital extensive. Other prominent technologies used for LVPs processing in to make other composite products, which struggle with product quality and acceptance in the market and for some it elongates the life of plastic use but not really make them circular in use.

Policy level challenges and limitations

Many countries have implemented bans on certain plastic products, such as single-use plastics, to combat plastic waste. Additionally, EPR schemes have been introduced, requiring manufacturers to take responsibility for the entire lifecycle of their products, including end-of-life disposal, use of recycled content and recycling. These policies aim to incentivize recycling and reduce the environmental impact of plastic waste. Furthermore, the ongoing discussions surrounding the International Negotiating Committee (INC) Plastic Treaty highlight the need for a coordinated global approach to plastic waste management, which could establish binding commitments for countries to reduce plastic production and improve recycling rates. However, the effectiveness of these policies often varies, and many low-value plastics remain unaddressed due to their complex composition and low economic viability for recycling.

In Indonesia, the policy framework related to plastic waste management is evolving, with recent regulations targeting low-value plastics. The government has recognized the urgent need to address plastic waste, leading to initiatives aimed at reducing plastic pollution. For instance, the Ministry of Environment and Forestry has launched campaigns to promote waste segregation and recycling, alongside regulations that encourage the reduction of single-use plastics. However, compliance and enforcement of these regulations remain significant challenges. Many local governments lack the resources and infrastructure to implement these policies effectively, leading to inconsistent enforcement and limited impact on reducing plastic waste. Moreover, the informal sector plays a crucial role in waste collection and recycling in Indonesia, but it often operates outside the regulatory framework.

Review of the existing technologies and methods for recycling low value plastics

This section aims to provide a structured comparison in assessing the technological performance and cost-effectiveness of recycling methods. Many recycling methods are already used for rigid (3D) and film (2D) plastic, the latter of which is considered as low-value plastic in the context of this study. The focus of the further analysis will be an assessment with regard to the suitability of the technological approaches presented for low-value plastic waste. The evaluation framework considers several key factors: technological feasibility, scalability, environmental impact, and economic viability. Technological feasibility examines each method's maturity and efficiency, ensuring it can effectively process low-value plastic waste. Scalability assesses the potential for these technologies to be implemented on a larger scale, which is crucial for addressing waste management challenges in Indonesia. Economic viability focuses on the costs associated with implementation, operation, and maintenance, as well as the potential for revenue generation or cost savings through material recovery and reuse. By systematically comparing these factors, this section provides an overview of the most promising recycling technologies, enabling us to make informed choices that balance technological innovation with economic and environmental considerations.

Systematic delimitations of plastic recycling technologies

The urgency to find solutions for the imminent plastic contamination of global ecosystems did lead to the creation of many concepts for plastic waste management and related terms and definitions globally. In order to not lose oversight over the used terms to describe those plastic management and recycling concepts it is important to define well the key definitions and delimitate them clearly from each other.

Plastic **recycling**, **upcycling**, and **downcycling** are crucial concepts in waste management and sustainability. Recycling involves converting waste into material that can substitute virgin material for the same application, upcycling transforms waste into products of higher value, while downcycling results in lower-quality materials. Differentiating these terms is essential for understanding the environmental impact and economic value of waste management strategies. Historically, recycling was seen as a simple process of substituting virgin by secondary materials, but as awareness of environmental issues grew, the concepts of upcycling and downcycling emerged to highlight the varying outcomes and benefits of different recycling methods. Upcycling is celebrated for its potential to create higher-value products and reduce resource consumption, whereas downcycling, though less ideal, still contributes to waste reduction by keeping materials out of landfills longer. These terms are used to advocate for more efficient and sustainable waste management practices, encouraging innovations that maximize material value and minimize environmental harm.

Analyzing recycling technologies for plastic waste makes a differentiation of these three terms important. Not always it can be stated clearly to which category a solution for plastic waste is belonging. Especially the term upcycling is not always used consistently as it is very much a matter of perspective. This depends for example on local market conditions, policy priorities and other factors. Figure 41 below is illustrating the output quality of the recycled plastic waste for recycling, downcycling and upcycling. Related to plastic waste the term upcycling is heavily criticized in the waste management sector to be used solely for marketing reasons because in general it is not really feasible to produce from waste something more valuable than the original virgin feedstock, due to thermodynamic principles. The energy and quality loss inherent in processing plastic waste means it is not feasible to transform it into products with higher value than the original material. To reach such upcycling a significant amount of energy would be required to reach improved quality criteria in addition the yield of such practices usually is very low. Consequently, while upcycling is often celebrated for its creative reuse, it is not a suitable large-scale solution for plastic waste management, as it cannot fundamentally alter the value loss inherent in recycling processes. On the contrary the term downcycling seems to be very suitable for certain plastic recycling solutions, where a lower quality output product is generated (for example of plastic replaces another material), as will be discussed in more detail further on.

Figure 41. Recycling versus Downcycling and Upcycling [71]

The following chapters will look primarily at typical plastic recycling solutions, the presentation will focus on their suitability for low-value plastic. As any recycling or upcycling requires intensive efforts in sorting beforehand many of the plastic recycling solutions presented will have to be classified as downcycling, because the output products are of lower quality than the original basic materials.

The systematic classification of different recycling technologies is not always uniform and in different scientific literature different terms and systems how to classify recycling technologies are used. Figure 42 below is giving a good overview about the delimitation between material recycling, chemical recycling, biological recycling and other plastic recovery solutions. Mechanical recycling – a subset of material recycling - and chemical recycling are the two big technological groups of closed loop recycling, whereby however just mechanical recycling technologies have yet reached commercial importance. Mechanical recycling together with the dissolution-precipitation recycling are summarized to physical or material recycling solutions, characterized by keeping the polymer chains intact during the recycling process. Chemical recycling of plastic waste involves breaking down the polymer chains, while mechanical recycling generally results in re-granulation of the plastic waste. The next chapters, which are describing different recycling technologies from a theoretical point of view, are following this systematic as shown in Figure 42 in order to allow a consistent description of recycling technologies. Biological recycling, also called bio-recycling technologies are rather unmature types of recycling and is shown in Figure 42 as Enzymolysis. It is discussed for reasons of completeness in the section on **Biological recycling** in more detail. They have no commercial relevance so far and are still in most cases in R&D stages of development.

In Figure 42 in grey colour the mechanical recycling is illustrated. For mechanical recycling many different technical set-ups have been developed, depending on the technology supplier, the type of final output (e.g. recyclate or final products) and the type of polymer, which is recycled. They have all in common that the building blocks of the plastic polymer are not disassembled, as it is the case for chemical recycling, and the output products are the same polymers, which did enter the mechanical recycling process. Due to this fact the energy intensity of mechanical recycling is less than that of chemical recycling.

Different options of chemical recycling, or often also called advanced recycling or molecular recycling, is shown in different colours. It summarizes a broad spectrum of technologies, which have in common that the recycled plastics are broken down into their principal building blocks, e.g. monomers or hydrocarbon molecules. This can be achieved by different means, as will be discussed in the corresponding sub-chapters. Dissolution has to be differentiated at this point. It can be seen also as a material plastic recycling technology, and in contrast to other chemical recycling technologies is not breaking down the polymers into monomers. That´s why it is not categorized as chemical recycling technology.

On the upper right corner of Figure 42 the group of other recovery options that also include options where plastic waste replaces other materials such as sand or gravel for example in construction products has been added. These recycling options are to be classified as downcycling or open loop recycling options and do have in common that the plastic will (most probably) be lost from the plastic material loop for further end of life cycles. Therefore, these recycling options can be seen as an extension of the linear economy plastic life cycle however they cannot be classified as circular economy type of option as the plastic as a material is lost from the plastics material cycle.

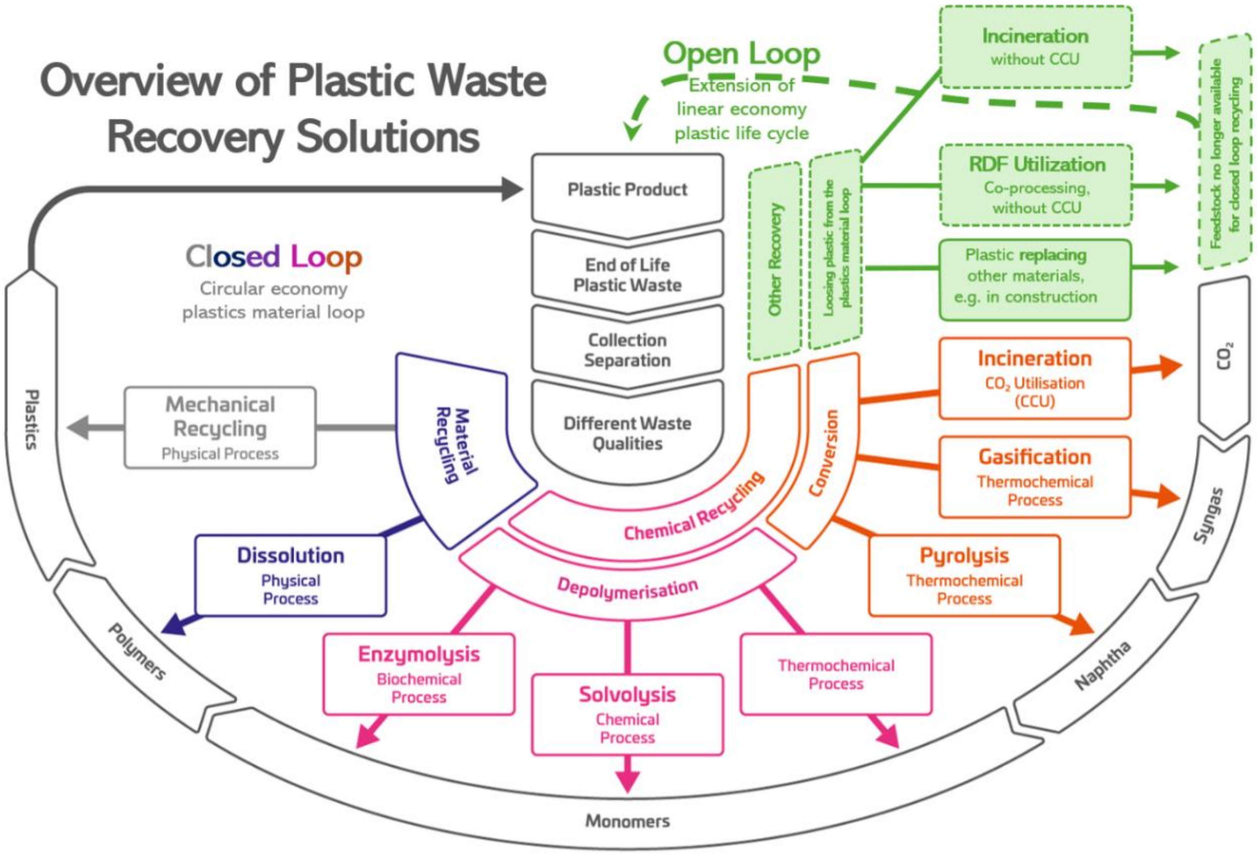


Figure 42. Overview of recycling technologies [8] (modified)

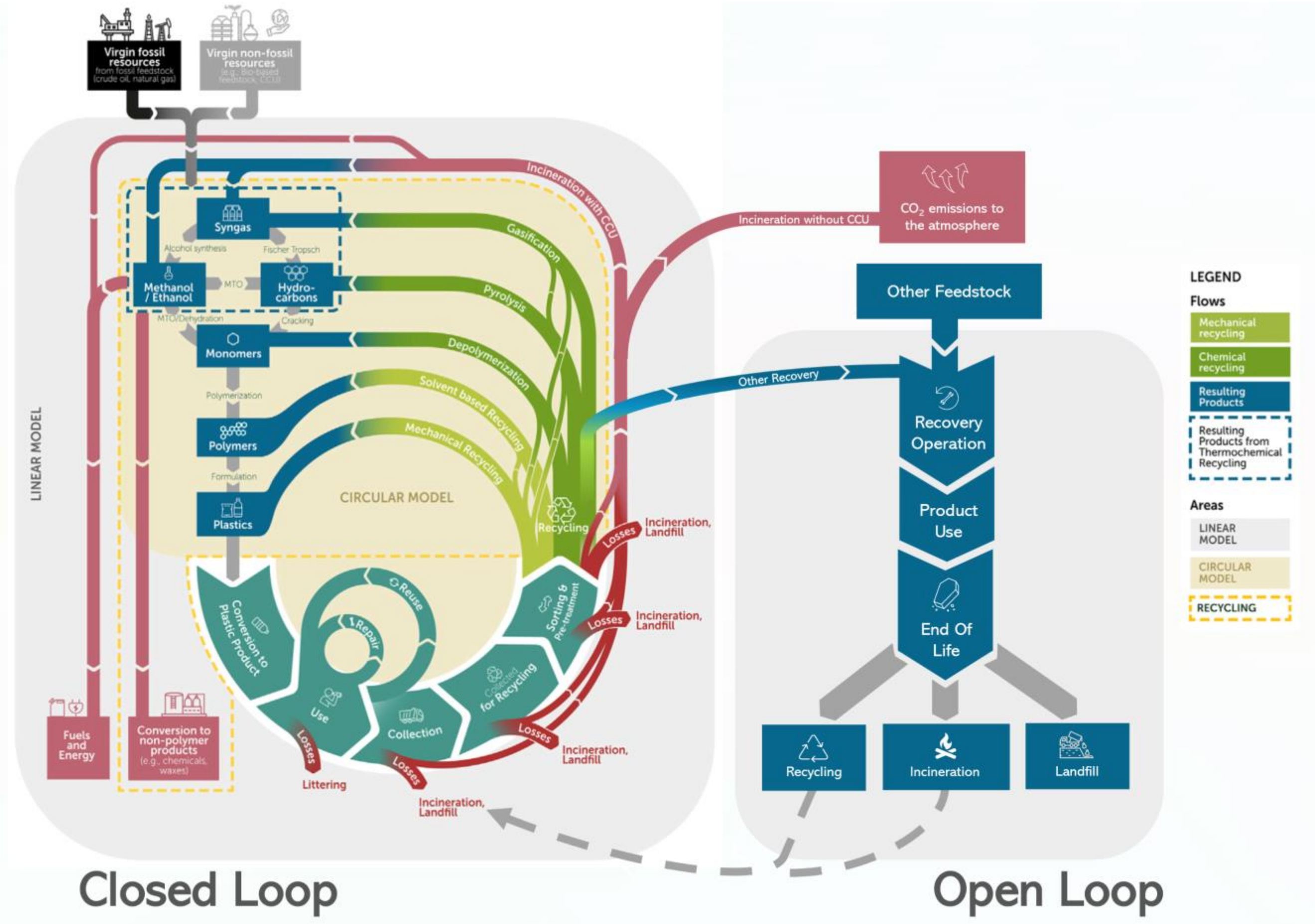


Figure 43. Plastic recycling terminology [1] (modified)

Similarly, Figure 43 shows the differentiation between closed loop and open loop recycling alternatives. Only if special precautions such as specific collection schemes and adapted processing are taken plastics from open loop recycling options can be recovered and re-introduced to the plastics material cycle again.

Figure 42 and Figure 43 are also illustrating what type of output product is generated by each technology and what type of chemical or physical process is involved. This is a very important point, because if plastic recycling is discussed it must be seen from a broad perspective including the complete plastic value chain. In general, the output products from chemical recycling are fed into the plastic value chain at a much earlier stage than, in comparison, the output products from mechanical recycling, because the polymers are dissembled in chemical base materials, which can be reused in the production of new polymers. Chemical recycling therefore is offering much more flexibility how the recycled molecules are used for further processing. This is a very important fact, which has a huge impact on the feasibility of advanced chemical recycling technologies, as will be discussed in detail further on.

The following chapters are giving an overview description of the main recycling paths which are shown in Figure 42.

Mechanical recycling

Under physical recycling technologies recycling methods are summarized, which allow that the polymer chains stay intact. This type of recycling is also called physical recycling. The most established recycling technology, the mechanical recycling, discussed in the next sub-chapters, belongs to this group. Based on the available recycling infrastructure in place and also the labour cost and the market readiness for recyclates different realisations of mechanical recycling are present around the world. We will differentiate between the following cases:

- **Industrialized approach:** This approach is implemented when there is a mature market for high quality recyclates, when technology is available and affordable and labour costs are high.
- **Social inclusion approach:** This approach is implemented when technology is hardly available and not affordable, labour costs are low and the market for recyclates are not yet developed.
- **Down-cycling approach:** This approach is implemented when plastic waste should be recycled into other types of products and if the feedstock and equipment is available.

The other relevant physical recycling solution based on solvents is Dissolution and Precipitation which is discussed in the section on **Dissolution and precipitation**. In addition to these two recycling technologies that aim for retaining the value of waste plastic for plastic applications there are recovery options offered on the market that aim for using the plastic waste as a substitute of something else. Aspects of these recovery approaches are discussed in the section on **Other recovery options.**

Mechanical recycling – Industrialised approach

Mechanical recycling encompasses several steps: sorting, cleaning, shredding, and further processing of plastic waste. The sorting step is a precondition for any type of recycling and has already been discussed in **Plastic waste sorting**. Therefore, the focus here is the subsequent steps of the mechanical recycling approach. Based on the setup and extent of sorting and cleaning beforehand different kinds of product might emanate from the recycling operation. Typically, mechanical recycling involves preparing the cleaned and sorted material through extrusion — a method where plastic is heated, melted in screw reactors, and forced through specialized nozzles to produce granules or plastic pellets. These granules / pellets can then be used to manufacture new plastic products in commonly used equipment. This approach allows for the biggest market for recyclates and the highest revenues for the produced recyclates.

Mechanical recycling often times focuses on the three dominant packaging polymers: PE, PP, and PET. The recycling process depends on carefully preprocessing involving sorting and cleaning in order to achieve pure monostream fractions, which are then compounded into granules. These granules are blended with virgin polymers of the same type, along with compatibilizers and additives, to address the limitations of the recycled material [72].

This recycling method is most suitable for thermoplastic materials that can melt during extrusion. It requires high-quality input materials free from impurities such as dirt, non-plastic materials, or other types of polymers. Effective recycling depends on separate collection and meticulous sorting by plastic type and colour to ensure the purity of the recycled material as well as achieving a high market value for the recyclates obtained. In developed recycling markets the revenue for these types of recyclates may even be higher than the price of virgin plastic compounds as the demand for recyclates from brand owners exceeds the quantity of recyclates brought to the market.

Figure 44 below is showing the plastic value chain for mechanical recycling. Here a differentiation between closed-loop recycling and open-loop recycling is made. Closed loop recycling means that the recycled polymer is used for the same product again, for example "PET bottle to PET bottle", whereas in the case of the open loop recycling a different product is produced from the recycled polymers. In this second case often, the recycled polymers cannot be used anymore for the same high-quality product, e.g. food-grade applications, and is now used for lower value products, like plastic bags, flowerpots, plastic park benches, etc. This downgrading of the recycled polymer has to do with contamination of the recycled polymer raw material or degradation of the polymer due to repeated recycling rounds.

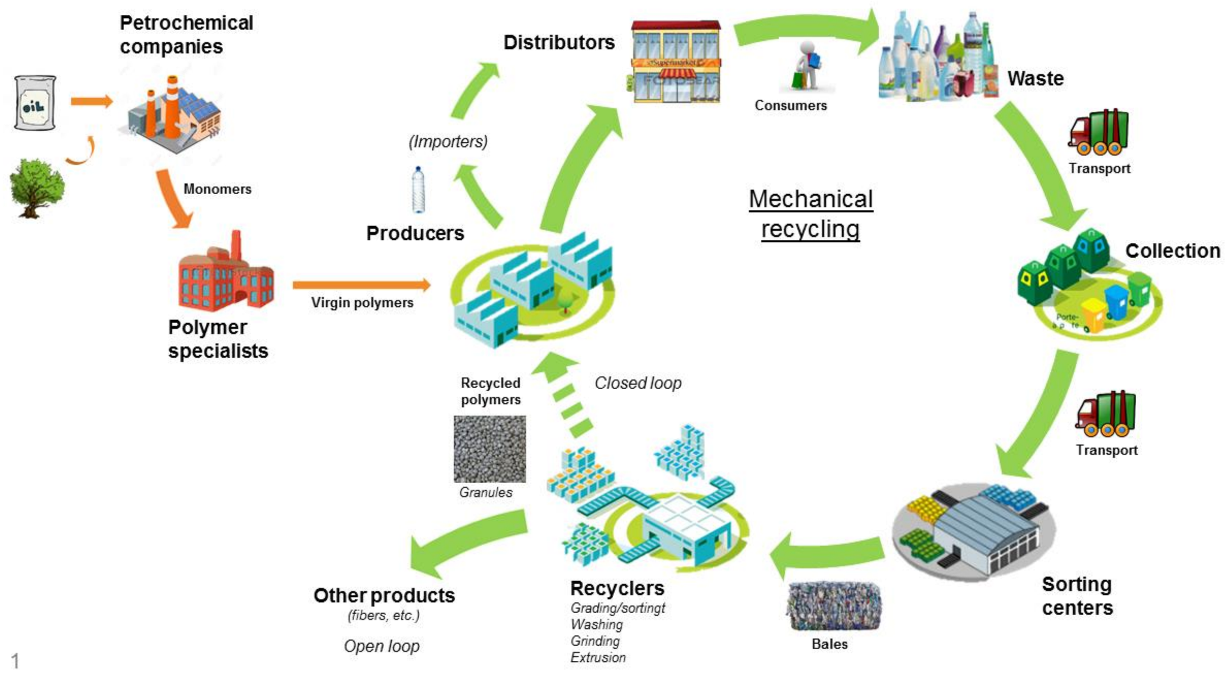


Figure 44. Plastic value chain for mechanical recycling [73]

The typical process steps for mechanical recycling are illustrated in Figure 45 below. A detailed description for the key process step is provided below.

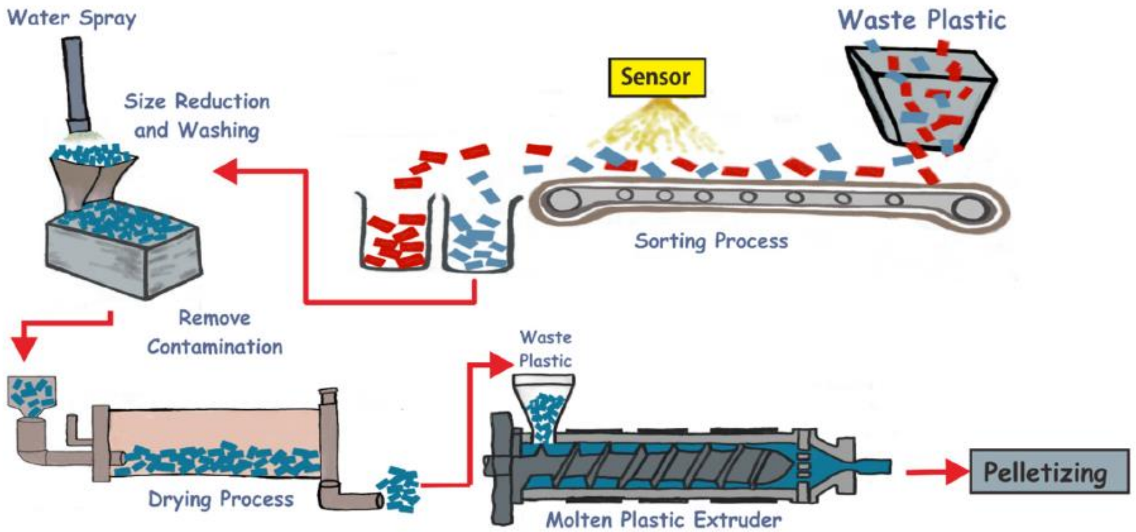


Figure 45. Process steps for mechanical recycling of plastic waste [21]

Sorting

The primary goal of the waste plastic sorting process is to achieve high-quality recycled plastic products, particularly from homogenous polymer streams. Sorting technologies rely on a range of chemical and physical properties of plastics, such as chemical composition, size, colour, and shape [21].

Modern optical sorting sensors are able to identify efficiently different polymer types via for instance NIR-sensors. Especially in places with low labour costs sorting may also be done manually at sorting stations. The importance of proper waste sorting has already been discussed in more detail in the section on **Plastic waste sorting.** In order to allow for an efficient sorting, the input stream requires conditioning. This involves the opening and emptying of bags used during the collection or transport, removal of undersize and oversize particles that cannot be handled during sorting and therefore need to be removed or undergo size reduction prior to sorting.

The output of the sorting stage are mono plastic fractions of typically purities above 95% of the target polymer. Many times, these fractions are also sorted according to colour in order to achieve a higher market value (compare Figure 46, left). However, for example PET-bottle waste fractions still contain contaminations from labels / sleeves and caps that are made out of other materials and that are fixed by adhesives as well as remaining content (compare Figure 46, right).

Figure 46. Out-put of the plastic waste sorting stage (left), remaining impurities like labels / sleeve with ink, cap (right) (photo-credit: Arne Ragossnig)

Shredding

At the next stage the waste objects are shredded or ground into smaller flakes. The main task here is to set free materials that need to be removed (i.e. labels, caps, etc.). It is important to note that the main sorting tasks needs to be done prior to shredding / grinding as the effort of sorting depends heavily on the number of particles to be sorted.

At that stage mainly shear shredders employing rotary cutters and guillotines to slice the plastic into uniform pieces that can easily be handled in subsequent processes and that meet industry size standards are being used. These methods ensure that the plastic is adequately prepared for the next stages of recycling [74].

Washing / Cleaning

After successfully sorting the various types of plastic waste, a crucial step in the recycling process is to thoroughly clean the shredded material as well as sort out impurities such as non-target polymers (PE-caps for PET bottles, paper, PE or PVC labels for PET bottles). This involves removing labels, residues, dirt, and other contaminants to ensure that the plastic waste is adequately prepared for further processing. Proper cleaning is essential to improve the quality of the recycled plastic and to make it suitable for recycling the secondary materials into the plastic value chain.

The output of this recycling stage is called flakes or ground material, is dry and with almost no impurities and looks like shown in Figure 47. Sometimes even the flake output is further sorted regarding the colour as especially transparent / light coloured mono-material fractions have a higher market price than a flake fraction with mixed colours. Depending on the subsequent processes even this flake product might directly be recycled into the plastic value chain without undergoing the next stage of extrusion & granulation.

Figure 47. Ground plastic material – flakes (three different types, mono-coloured flakes have a higher market value when compared to mixed coloured flakes) (photo-credit: Arne Ragossnig)

Extrusion & Granulation

The extrusion and granulation processes are essential for converting plastic materials into a form suitable to be directly used for so called converters who use virgin plastic pellets to produce films or other plastic products with ordinary standard from the shelve equipment. At that stage also additives such as colourants or other chemicals influencing the final properties of the plastic compound to be marketed may be added.

Initially, the plastic undergoes extrusion to create strands or a continuous solid polymer product by heating and passing it through a die. These strands are then cut to pellets and subsequently cooled in a water bath.

In Figure 48 the output of the extrusion stage can be seen. As discussed above these pellets can now be sold and used to produce new plastic products substituting virgin plastic pellets.

Figure 48. Plastic pellets (photo-credit: Arne Ragossnig)

As part of the washing / cleaning stage as well as the extrusion stage different types of technologies might be employed to ensure that remaining smells and contaminations from the use stage of the plastics to be recycled are removed. If these types of technologies are applied the final plastic pellets might as well be used in food-grade applications.

Technology examples for this recycling approaches are the following:

- Triplast: Based in Austria, Triplast is operating a large-scale sorting and mechanical recycling project in Upper Austria with a capacity of 100.000 tonnes of plastic waste per year, the plant has started operation in mid 2024. (https://triplast.at/)
- LVP-sorting plant Ölbronn: This plant was built by SUEZ and started operation in 2019. It has a capacity of 125,000 t/a, in 2022 operation was taken over by PreZero
- Swedish Plastic Recycling: Operates in Sweden the largest plastic recycling plant in Europe – site zero, the capacity for mixed plastics is 200,000 t/a that is sorted to 12 output streams (https://www.svenskplastatervinning.se/en/site-zero/)

Mechanical recycling – social inclusion approach

In many parts of the world – especially the Global South – where heavy investments into sorting & recycling equipment are not feasible, the recycling activities are being dominated by the informal sector and at the same time labour costs are comparable low the processes for mechanical recycling might look a little different.

Nevertheless, the collection of the plastic waste to be recycled is the first stage. Other than focusing for example on packaging waste as a whole as it is often done in the Global North as a consequence of EPR systems that have been established already 30 years ago, the collection activities of the informal sector many times already involve a very selective approach, meaning that for example only PET bottles are being collected. All the rest of the (plastic) waste is left to be dealt with by the ordinary waste management processes in place.

Whenever the collection is done that way the subsequent sorting process requires less effort. Figure 49 shows the quality of PET collected by the informal sector as well as the subsequent manual de-labelling. From there on size reduction is key to allow for the implementation of recycling processes that are discussed in more detail later-on.

Figure 49. PET bottles collected by the informal sector, manual de-labelling (photo-credit: Sam Tarema)

Technology examples for this recycling approaches are the following:

- Botellas de Amor: This Colombian NGO is promoting the collection and use of plastic waste and its transformation in usable products for communities, like toys for playgrounds (https://botellasdeamor.org/)
- Bamboo House India: Social Enterprise from India, which is offering small scale plastic recycling solutions for the production of products for daily use: (https://www.bamboohouseindia.org/)
- EcoBrixs: an Ugandan enterprise producing many different day-to day products out of plastic waste (www.ecobrixs.org/eco-products)

Mechanical recycling – downcycling approach

Sometimes, especially in a Global South context, a mix of plastic waste is processed and finally used to mould products that can be sold on the market (i.e. park-benches, fence-poles, combs, dishes, decorative elements, etc.). It must be clearly stated whereby this latter approach has its benefits with regard to social inclusion and fosters entrepreneurship it cannot be conceived as a viable solution to solve the plastic waste challenge at large, it also is to be seen as a downcycling solution, however, the material properties of plastics are kept alive and these objects produced out of the mixed plastic at the end of their lifetime may be chemically recycled.

Technology examples for this recycling approaches are the following:

- Plasticpreneur: An Austrian company which developed and sells small plastic extruders and other plug-in-and-play plastic recycling machines, which are suitable to process on a small scale mixed plastic waste and transform it in suitable products for daily use, like combs, coat hangers, etc. (https://plasticpreneur.com/)
- Bamboo House India: Social Enterprise from India, which is offering small scale plastic recycling solutions for the production of products for daily use: (https://www.bamboohouseindia.org/)
- EcoBrixs: An Ugandan enterprise producing many different day-to day products out of plastic waste (https://www.ecobrixs.org)
- TrashCon: An Indian company offering simple waste sorting machines and mechanical recycling solutions for low-income countries. (https://trashcon.in/)

Strengths of mechanical recycling

The main strength of mechanical recycling lies in the closed loop and therefore low energy demand for the process. Compared to virgin fossil oil-based plastic pellet production mechanical recycling and the provision of recycled plastic pellets involves just about 10 – 20% of the energy demand which also includes a carbon footprint that is also lowered by that extent [75].

Therefore, mechanical plastic recycling stands out for its energy efficiency and environmental benefits. Compared to the production of virgin plastics, mechanical recycling significantly reduces energy consumption, as it requires lower energy inputs due to the pre-existing polymer chains in recycled materials.

Another one of the key advantages of mechanical recycling is its ability to conserve valuable natural resources. By reprocessing plastic waste, the demand for virgin plastics derived from non-renewable fossil fuels is reduced. This conservation of finite resources aligns with global efforts to decrease reliance on petroleum and other non-renewable energy resources.

Mechanical recycling also plays a crucial role in waste reduction. By diverting plastic waste from landfills and incineration, it alleviates the pressure on waste management systems and helps prevent environmental pollution. The transformation of plastic waste into reusable materials contributes to reducing the negative impacts of plastic pollution, such as marine debris and habitat destruction.

Economically, mechanical recycling fosters job creation and stimulates innovation within the recycling industry. The process also supports the creation of closed-loop systems, where recycled materials are reintegrated into the production process to manufacture new products. This approach not only reduces the environmental footprint of consumer goods but also promotes circularity by minimizing waste generation and maximizing resource efficiency.

Furthermore, the increasing consumer demand for sustainable products has driven businesses to adopt mechanical recycling as part of their corporate responsibility initiatives. Companies are now integrating recycled materials into their products to meet the growing expectations for eco-friendly and socially responsible options, thereby driving the market demand for recycled plastics.

In summary, mechanical recycling offers a robust solution for plastic waste management.

Limitations of mechanical recycling

Conventional mechanical recycling of plastic waste struggles to effectively reduce plastic pollution due to a combination of technical and economic challenges. A major limitation of mechanical recycling is that it can only process certain homogeneous plastic streams and requires extensive presorting and cleaning. The infrastructure for this, especially in developing nations, rarely exists. As a result, it remains unsuitable for a significant portion of collected end-of-life plastics, especially plastic waste in mixed waste streams. Typical thermoplastic polymers, which are processed via mechanical recycling, are PET, PP, HDPE. Mechanical recycling faces other limitations to address the vast variety of plastic types on the market. It is for example not feasible for composite or multi-layer plastic materials, nor for thermoset and elastomer polymers due to their complex compositions and properties. In addition, if the input plastic is not sorted well enough the feed may contain polymers or other substances with a lower melting point that might thermally degrade in the melt at the operating temperature of the extrusion and form contaminations such as Polycyclic Aromatic Hydrocarbons (PAH´s) during that process.

Contamination of one polymer type within another typically degrades mechanical properties and creates reprocessing issues. Since polymers are typically immiscible with each other, impurities from different polymers tend to segregate into small foreign domains within the recycled material, creating weak spots [72]. Therefore, it is of utmost importance for mechanical recycling project, that the pre-processing of waste guarantees homogenous and clean polymer waste streams. For example, mixing PET with PVC is problematic because at PET's processing temperature, PVC degrades and releases corrosive hydrogen chloride gas, while PET does not melt at PVC's processing temperature. Therefore, accurate and cost-effective sorting methods are essential and should be further developed to prevent such contamination [76].

Another major issue is the degradation of recycled polymers during reprocessing, which diminishes their performance properties. This degradation makes recycled plastics less competitive compared to virgin plastics, which possess optimal performance characteristics and new additives. The cost of improving recycled plastic quality to match that of virgin plastic is a significant economic hurdle for the industry. This is one of the main reasons why the feasibility of plastic recycling is very much dependent on the commodity price developments of fossil raw materials, e.g. crude oil price, due to its direct impact on the competitiveness of recycled polymers. The degradation of recycled polymers is usually dealt with by enhancing the quality of the compound by adding additives or else by mixing recycled with virgin plastic pellets in order to meet the requirements set.

While mechanical recycling has proven to be efficient and successful, it is typically limited to a few cycles and relies on the purest and cleanest waste streams. Actually, this is very much dependent on the recycling infrastructure in place. In settings where the plastic market not yet relies on recyclates for example, PET is generally recycled or downcycled once, from bottles to textiles. PP, although technically capable of supporting up to four recycling cycles, is practically recycled or downcycled just once, often into textiles and playground equipment. This process mainly results in downcycling. Therefore, there is a growing need for complementary recycling options, particularly chemical recycling [72].

While some polymers, like PET and HDPE, are recycled commercially, they also face limitations such as contamination and the presence of additives, leading to quality degradation with each recycling cycle. This results in a loss of recyclability over time that usually needs to be compensated by using additives to create compounds meeting the specifications. Technical issues include the reliance on chemical additives that hinder recycling, immiscibility with other polymers, contamination during the consumer phase, and thermal and mechanical degradation during processing. These factors often lead to downcycling, where high-quality plastics are recycled into lower-value products, which eventually become unrecyclable waste. This issue is particularly problematic for food-grade and contact-sensitive plastic applications. Although there are some technologies capable of producing high-purity mechanical recycling outputs suitable for food-grade uses, such as PET and potentially polystyrene, mechanical recycling often struggles to meet the stringent requirements for these applications in many other cases [77].

Additives and contaminants in mechanical recycling can be addressed by removing them through processes such as extraction or dissolution/reprecipitation. In extraction, the waste polymer is washed with a suitable solvent or supercritical fluid that has a high affinity for the additive, dissolving it. However, this method may struggle to remove a wide variety of additives with different solubility properties, necessitating more complex solutions like dissolution/reprecipitation, which is discussed in the following sub-chapter in more detail. In dissolution/reprecipitation, the spent polymer is completely dissolved in a suitable solvent. The solution is then separated from insoluble impurities and additives, and the polymer is reprecipitated by adding an antisolvent. The solvent and antisolvent are subsequently recovered for reuse. This recovery process is energy-intensive, especially when operating with a high solvent/polymer ratio. Therefore, it is crucial to ensure that the energy required for solvent evaporation is significantly lower than that needed to depolymerize the polymer back to its monomer [72].

Thermal mechanical degradation, caused by heating and mechanical shearing during melt processing, results in changes to the polymer chain, such as chain scission or branching, which reduces molecular weight and functional properties, complicating recycling. Additives in plastics, used for various functional properties, further complicate recycling. Some additives are hazardous, and their degradation products can contaminate recycled plastics, reducing their quality and marketability.

The presence of non-intentionally added substances, impurities, and reaction products formed during polymer production also poses problems, especially for products with high human exposure potential. Additionally, mixtures of additives can reduce the compatibility of different waste streams, even within the same polymer type, leading to immiscibility issues that hinder successful recycling.

Efforts to improve miscibility through chemical compatibilizers have seen some success but have not fully resolved the problem. The addition of compatibilizers and additives to blend recycled materials with virgin resin increases the impurity levels in the recycled resins. Over multiple recycling loops, this accumulation of impurities will eventually disqualify the material from further mechanical recycling. At this stage, more sophisticated recycling technologies, such as dissolution/precipitation or chemical recycling, will be necessary to continue the recycling of such polymers [72]. The growing use of bioplastics, such as PLA, adds another layer of complexity, as they are incompatible with traditional plastics like PET, further complicating recycling processes [78].

While mechanical recycling holds potential for advancements through innovation, better recycling-oriented design, and improved collection and sorting methods, it is probable that certain waste streams will remain unsuitable for mechanical recycling. This is especially true when high-quality output is needed [77].

Lastly, it is also important to mention that mechanical recycling is not infinitely sustainable for the same polymers. Over successive recycling cycles, material aging and the persistence of impurities can degrade the quality of the recycled product. This means, that mechanical recycling often means a downcycling of the polymer, because a closed-loop recycling, where the same product qualities for the same final plastic product are needed, is seldomly achieved. Often the polymers are used after the recycling for non-food-grade applications. E.g. PET plastic bottles are downcycled to textile fibers, PP polymers are downcycled to textiles or playground equipment

[72]. These factors underscore the need for ongoing innovation in recycling technologies and improved waste management practices to enhance the sustainability of plastic recycling efforts.

Dissolution and precipitation

Another recycling solution, which is summarized together with mechanical recycling to the group of physical recycling technologies, where the polymer chains stay intact, is solvent-based dissolution–precipitation, an innovative "plastic-to-plastic" recycling technology that facilitates a circular economy in a single step. Unlike other recycling methods such as depolymerization, pyrolysis, or gasification, which require multiple processing steps to recreate plastics, this process is more streamlined. In the dissolution–precipitation process, post-consumer or post-industrial waste plastics are dissolved in a solvent. This is followed by a filtration step to remove any undissolved contaminants, such as dirt, fillers, and other polymers. The polymers stay intact and are not disassembled into monomers, as it is the case with chemical recycling technologies.

The dissolved polymer can then be recovered as a pure resin through one of three methods: adding an anti-solvent, evaporating the solvent from the polymer solution, or reducing the temperature of the polymer solution to precipitate the polymer. This recycling technology has several advantages over traditional mechanical recycling methods, including higher product yields. Additionally, it is capable of processing multi-layered plastics, which are typically challenging to handle with mechanical recycling. This is discussed in the next sub-section—**Strengths of dissolution and precipitation-based recycling.**

Many plastic packaging materials manufactured today are composites made of distinct polymer layers, known as multi-layer films. Each layer in a multi-layer plastic product is chosen for specific properties that enhance the functionality of the overall packaging solution, such as providing moisture or oxygen barriers. The complexity of these materials is further increased by the inclusion of tie layers, these are adhesives between the layers, which typically constitute less than 1% of the total material weight. Recycling multilayer films is challenging because they cannot be recycled mechanically by state-of-the-art recycling processes. Multilayer packaging provides numerous benefits for products and consumers, making a ban on its use impractical and unwise. Instead, the most feasible strategy is to develop suitable recycling processes for this type of packaging. Recent years have seen several studies focused on recycling multilayer packaging, with many of these processes involving the use of solvents [79].

Due to the complexity of its structure and materials, along with the limitations of existing recycling frameworks, multilayer packaging cannot currently be recycled on a commercial scale. This creates significant challenges for achieving a circular economy. Each layer must be separated and then reconstructed individually. Currently, no commercially viable technologies exist that can accomplish this.

Annually, billions of tonnes of these multi-layer films are produced. Although this waste is relatively clean and of near-constant composition, no commercially practiced technologies currently exist to fully deconstruct postindustrial multi-layer film wastes into pure, recyclable polymers.

Figure 50 shows the three different recovery methods exemplary for PET recycling via dissolution-precipitation.

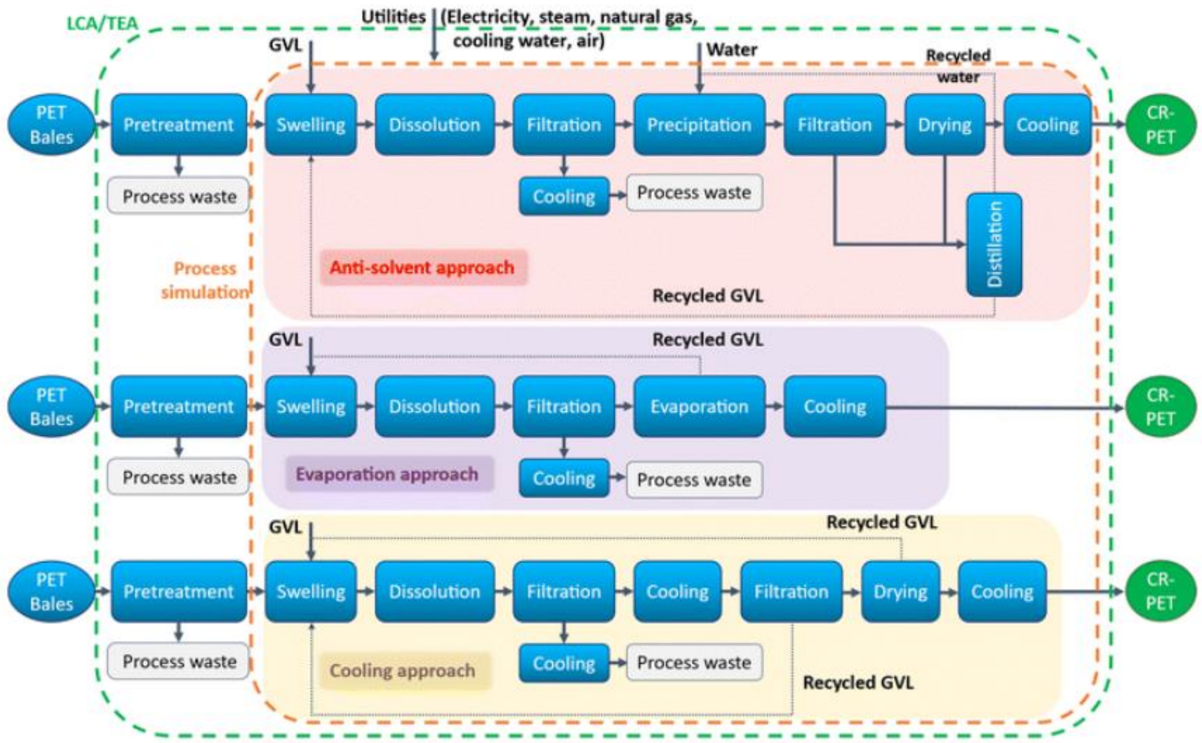


Figure 50. Solvent based dissolution-precipitation processes for waste PET with different polymer recovery approaches [80]

Overall researchers claim that solvent-based dissolution–precipitation offers a more efficient and versatile approach to recycling plastics, contributing to a more sustainable and circular economy by effectively transforming waste plastics back into high-quality plastic polymers [80].

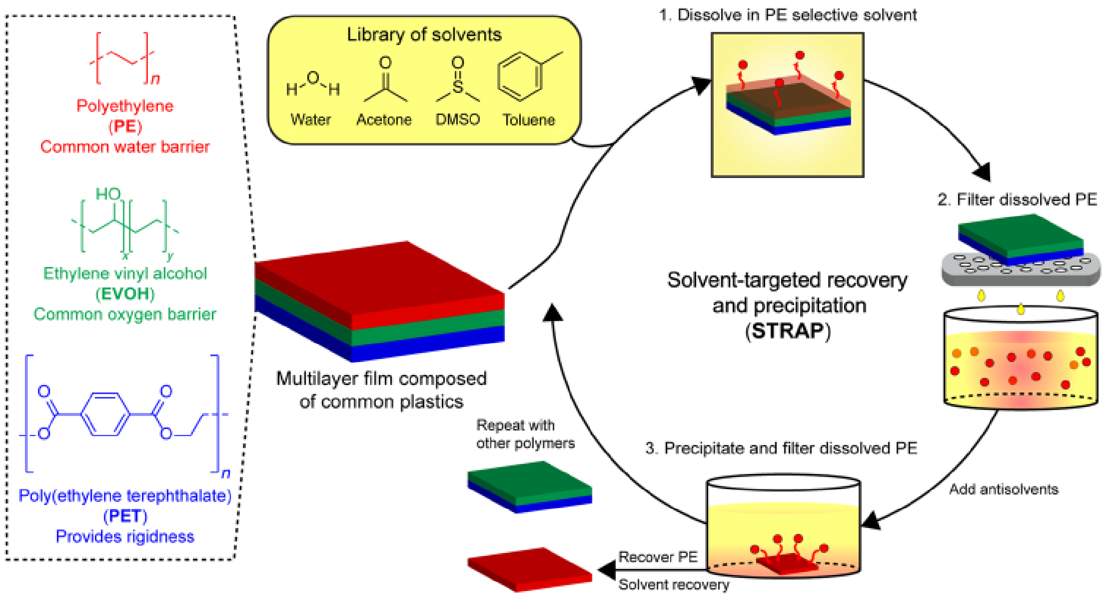


Figure 51. Solvent-targeted recovery and precipitation (STRAP) process for multilayer packaging plastics [81]

With solvent-targeted recovery and precipitation (STRAP) a new method for effective deconstructing multi-layer films into their constituent resins has been developed. This process involves a series of solvent washes, guided by thermodynamic calculations of polymer solubility, to separate the different polymer layers. The STRAP process has been shown to successfully separate three representative polymers — polyethylene, ethylene vinyl alcohol, and polyethylene terephthalate — from a commercially available multi-layer film with nearly 100% material efficiency [82]. An overview about the STRAP process is shown in Figure 51.

Technology examples for this recycling technology are the following:

- Creasolve: the Creasolve process has been developed by the Fraunhofer Institute (https://www.creasolv.de/de/). Recently a first pilot plant of industrial scale has been implemented in Germany.
- Purecycle: This US-based technology focusses on PP. First industrial scale production facility has been set up in Ironton Ohio, recently (https://www.purecycle.com/)
- Newcycling: This German based technology provider focusses on LDPE. First industrial scale production has been done in 2016 (https://www.apk.group/en/newcycling/)

Strengths of dissolution and precipitation-based recycling

Dissolution and precipitation recycling offers a promising approach to address the challenges posed by traditional mechanical recycling methods. This advanced technology excels at recovering high-purity materials from complex waste streams, particularly multi-layered plastics, which are notoriously difficult to process using conventional techniques. By dissolving plastic waste in a carefully selected solvent and subsequently precipitating the desired polymer, this method achieves near-perfect material separation, resulting in high-quality recycled resins. This closed-loop process effectively eliminates the need for downcycling, a common issue in mechanical recycling, and ensures that the recovered materials can be directly reincorporated into the production of new plastic products. Furthermore, the technology demonstrates significant energy efficiency benefits. For example, compared to the energy required to produce virgin PET resin, the dissolution and precipitation process consumes approximately 37% less energy [83]. Although the energy savings are lower when compared to mechanical recycling the dissolution and precipitation-based recycling offers still a huge ecological advantage over the life cycle compared to not recycle the plastic.

This reduction in energy consumption translates to lower greenhouse gas emissions, making it a more sustainable option than other waste management options and even incineration. Economic analysis indicates that the dissolution and precipitation process is commercially viable, with the potential to produce recycled resins at a cost competitive with virgin materials [84]. This economic feasibility, coupled with its environmental advantages, positions this technology as a strong contender for large-scale implementation in the plastics recycling industry.

Limitations of dissolution and precipitation-based recycling

While dissolution and precipitation-based recycling offers promising potential for addressing plastic waste recycling challenges, it is essential to recognize the inherent complexities and limitations associated with this technology.

Solvent Selection and Process Complexity

A critical hurdle in implementing dissolution and precipitation-based recycling is the identification of suitable solvent systems capable of selectively dissolving individual polymer layers within complex multilayer films. Given the vast array of industrial solvents and the intricate composition of many plastic films, selecting the optimal solvent or solvent mixture often necessitates extensive experimentation.

Furthermore, the presence of tie layers and additives within plastic films can significantly complicate the separation process. These components, often present in trace amounts, can interfere with the dissolution and precipitation steps, requiring additional process steps or treatments to ensure the purity of the recovered polymers.

Solvent Recovery and Residual Contamination

The effective recovery of solvents is essential for the economic viability and environmental sustainability of dissolution and precipitation-based recycling. Solvent losses through evaporation, degradation, or contamination can increase operating costs and environmental impact. Developing efficient solvent recovery systems is crucial to minimize these losses.

Additionally, trace amounts of residual solvent may remain in the recovered polymers, potentially affecting their properties and limiting their applicability in certain applications, such as food packaging. Rigorous purification processes are necessary to ensure the safety and suitability of recycled polymers.

Economic Feasibility and Scalability

The economic viability of dissolution and precipitation-based recycling depends on several factors, including the cost of solvents, energy consumption, and the value of recovered materials. While the technology has demonstrated promise in laboratory and pilot-scale studies, scaling up the process to commercial levels may present challenges in terms of equipment, infrastructure, and operational costs.

Moreover, the variability of plastic waste streams in terms of composition and contamination levels can impact the efficiency and cost-effectiveness of the recycling process. Developing robust and adaptable systems to handle diverse waste streams is crucial for the successful implementation of this technology.

In conclusion, while dissolution and precipitation-based recycling offers significant advantages, overcoming the challenges associated with solvent selection, solvent recovery, and economic feasibility is essential for the widespread adoption of this technology. Continued research and development efforts are needed to address these limitations and optimize the process for commercialization.

Other recovery options

In this chapter other types of recovery that do not focus on recycling the plastic into the plastics value chain but focus on substituting other materials by plastics shall be mentioned. These technologies cannot be considered as recycling option for plastics; however, they still recover the plastic to replace another material and should therefore be seen as a more desirable waste management option than open burning, open dumping or landfilling as long as they do not cause a new environmental problem harming the environment. These alternative approaches do not constitute recycling in the narrow sense, they offer a temporary solution to manage plastic waste more sustainably by extending its lifecycle. Such solutions might be acceptable under certain circumstances, particularly in developing nations where advanced waste management and recycling systems are still being established. By using downcycling as a bridge solution, these regions can alleviate the immediate environmental impact of plastic waste while working towards the implementation of more sophisticated recycling technologies and comprehensive waste management systems.

There is proposals and also practices to use plastic waste as an addition to asphalt for building roads or to use plastic flakes as a replacement of bitumen in asphalt [85] or even as a replacement of aggregate in concrete [86]. All these approaches must be assessed based on a life cycle perspective on a system level. Aspects such as micro-plastic release to the environment through degradation based on weathering or mechanical wear and tear with the subsequent release of the microplastic particles to the environment, and finally their entering into the food-chain as well as the material loss for future recycling must be considered.

In the following subchapters the most common alternative plastic waste management solutions are discussed. In the plastic recycling comparison section of this present study in the section on **Technology comparison**, these solutions have been included in order to include them in the assessment regarding its suitability for contributing to solve the plastic pollution problem in developing nations.

Utilisation of thermoplastic waste in the construction of bricks, tiles and blocks

The use of thermoplastic wastes in constructing bricks, tiles, and blocks involves integrating plastic waste into building materials, providing a potential solution for managing large volumes of plastic waste. This can be achieved by shredding and melting thermoplastic waste, which is then mixed with traditional construction materials like sand and cement to create composite materials. These plastic-enhanced construction materials can offer benefits such as improved insulation properties, reduced weight, and enhanced durability. However, these material properties have to be assessed and have to meet certain specifications. Many times, when such recycling options are being proposed the focus of the technology providers is solely laid at meeting certain stress-related specifications such as compressive strengths or tensile strengths and these arguments are used for marketing purposes.

Aspects that relate to the environmental performance are oftentimes neglected. However, several environmental and health concerns must be addressed. The incorporation of thermoplastic wastes can lead to the release of microplastics into the environment, posing long-term ecological risks. Health issues may arise from the potential leaching or release of toxic substances and volatile organic compounds during the product's lifecycle. Additionally, ensuring fire protection is critical, as thermoplastics are inherently flammable and can compromise the safety of structures. Another significant challenge is the difficulty of further recycling the plastic within these construction materials, making it a less viable contribution to the circular economy.

The addition of plastics to minerals in order to create new products not only results in the loss of plastic from the plastic value chain making it almost impossible to recover the plastic again, but also impedes the recycling of the minerals used for the newly created materials. Resources embedded in these products might therefore be lost in the long term, as the thermoplastics become inseparable from the mineral matrix, thus preventing their future recovery and reuse. While this method provides a promising avenue for managing plastic waste, comprehensive strategies must be developed to mitigate its associated risks and ensure sustainable and safe application in construction.

Technology examples for this recycling approaches are the following:

- Keybricks: This company is based in South Africa and selling building materials, which are produced by adding plastic waste. (https://keybricks.co.za/)
- Ecobrix: Based in Uganda following a community-driven approach to tackling Plastic Waste by production of building materials (https://www.ecobrixs.org/)
- Rebricks: Based in Indonesia, using plastic waste for the production of building materials, like bricks (https://rebricks.id/)

Utilisation of thermoplastic waste in concrete and road construction

The utilization of thermoplastic wastes in concrete and road construction presents a novel method for addressing the plastic waste crisis while improving infrastructure. This involves incorporating shredded or melted thermoplastic waste into asphalt and concrete mixtures, enhancing the flexibility, durability, and lifespan of roads and structures. By doing so, this approach can reduce the reliance on traditional raw materials like bitumen and aggregates, offering a more sustainable and cost-effective alternative for construction projects.

However, this innovative use of plastic waste brings several challenges and environmental concerns. One of the primary issues is the potential release of microplastics into the environment, which can have long-term ecological impacts. Additionally, the leaching of toxic substances and volatile organic compounds from the plastic waste during the construction and usage phases poses significant health risks.

Furthermore, the integration of thermoplastic waste into concrete and asphalt complicates future recycling efforts. Once embedded in these materials, the plastic becomes difficult to separate, leading to a potential loss of valuable resources and hindering the transition to a circular economy. While the incorporation of thermoplastic waste in concrete and road construction offers promising benefits, it is essential to develop comprehensive strategies to mitigate these risks and ensure that this approach contributes to a more sustainable and efficient waste management system.

Technology examples for this recycling approaches are the following:

- ECOPALS: Based in Germany. Their main product are EcoFlakes, which are made out of plastic waste and are used for the construction of roads by mixing them with asphalt. (https://www.ecopals.de/)
- University of Texas at Arlington: Sahadat Hossain, a civil engineering professor is using both recycled and unrecycled plastic waste products to fill in surface cracks and reduce rutting in roads—the first use of what's called "plastic road" material in Texas. (https://www.uta.edu/news/news-releases/2023/02/06/hossain-plastic-roads), this practice is also implemented in Bangla Desh and India)

Chemical recycling

Chemical recycling is a broad field comprising numerous technologies that utilize solvents, heat, enzymes, and even sound waves to purify or break down plastic waste into polymers, monomers, oligomers, or hydrocarbons. This sector includes purification, depolymerization, and conversion technologies capable of processing various plastic wastes, such as packaging, textiles, healthcare plastics, and wind turbine blades. Incineration is also considered as a chemical recycling route, if the carbon content from the flue gas is captured and reutilized for the production of polymers but is not in detail disused in the present study.

These technologies offer solutions for plastics that currently lack end-of-use recovery options, extending beyond just packaging recycling to recover a diverse array of materials. Examples of plastics which could be recycled via chemical recycling are multilayer plastics, thermoset plastics or composite plastics.

Chemical recycling of plastic waste streams is being actively researched by numerous companies and institutes, with the aim of understanding its potential future role in managing plastic waste and its various technological advantages and disadvantages. However, chemical recycling is seen by many waste management experts controversial, and the lack of practical, industrial-scale, and long-term experience makes it challenging to scientifically and technically evaluate the diverse approaches, which are proposed for chemical recycling. Market analysis show that large companies from the polymer production and chemical industries in particular are making strategic investments in the field of chemical recycling. They have a strategic interest in chemical recycling solutions to access secondary raw materials streams, which they easily can incorporate in their current production facilities, and they also can address with such solutions the pressure from civil society and environmental groups to contribute to solve global plastic pollution [87].

Since plastics are largely decomposed during chemical recycling processes, there is potential to either precipitate or destroy contained impurities and pollutants. Thermal processes at higher temperatures, particularly gasification and incineration, can effectively destroy organic pollutants as well. Contaminants transferred to products, such as heavy metals, salts, inorganic gases, or stable organic compounds, can be removed during further processing, thereby being withdrawn from the cycle. Oils produced through liquefaction and pyrolysis can be treated by hydrogenation, while gases from gasification and combustion are purified using appropriate gas cleaning systems. Consequently, chemical and thermochemical processes have the potential to remove pollutants during recycling, unlike mechanical recycling methods [8].

An important differentiation in the categorization of chemical plastic recycling technologies has to be done between Thermolysis and Solvolysis chemical plastic recycling technologies. This is illustrated in Figure 52 below.

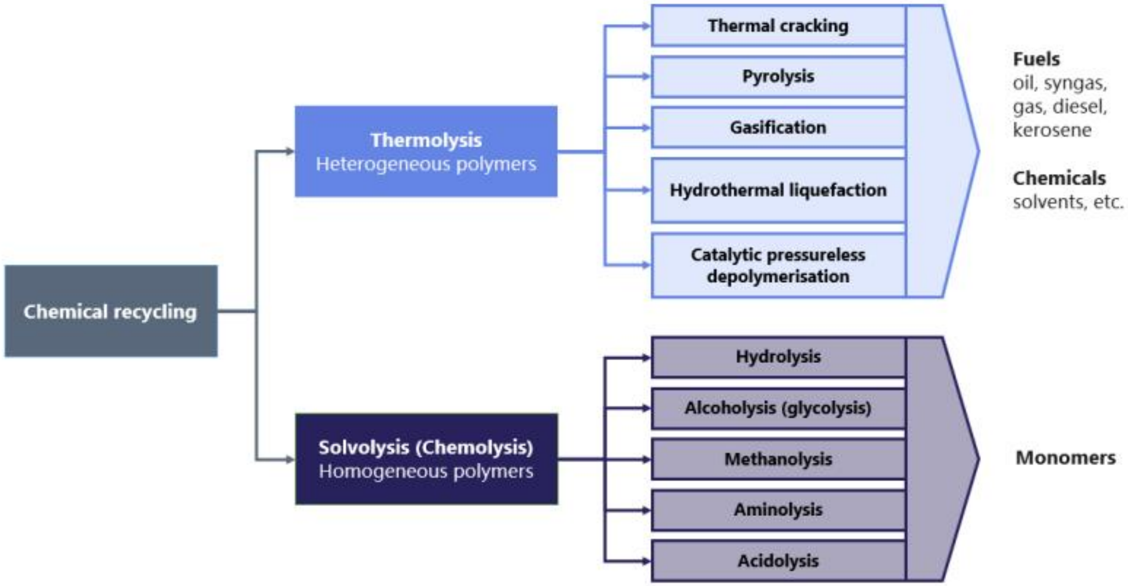


Figure 52. Differentiation between Thermolysis and Solvolysis chemical plastic recycling technologies [88]

The first category involves converting plastic waste into fuels through thermolysis, also known as "plastic-to-fuels" technologies. Examples of thermolysis processes include thermal cracking, pyrolysis, gasification, hydrothermal liquefaction, and catalytic pressureless depolymerization. Thermolysis of plastic waste requires high temperatures, which consume a significant portion of the energy contained in the plastics. Due to these high energy demands and the focus on producing fuels rather than materials, the classification of thermolysis as a recycling process is often considered controversial.

The second category of chemical recycling technologies, known as solvolysis or "plastic-to-plastic" chemical recycling, converts plastic waste into monomers that serve as feedstock for new polymers. This process includes methods like hydrolysis, alcoholysis, methanolysis, glycolysis, and aminolysis. Unlike thermolysis, plastic-to-plastic recycling is less controversial because it has the potential to reduce the demand for new virgin polymers. Solvolysis aims to address the main challenge of mechanical recycling—downcycling—by producing polymers that are identical to the original materials. Plastic-to-plastic technologies are still emerging and are less developed compared to the more advanced "plastic-to-fuels" conversion techniques [88].

The following sub-chapters are summarizing the typical process parameters, product categories and challenges and opportunities for the most important chemical recycling technologies, as shown in Figure 52. There are many other chemical recycling technologies in development, but they are still in an early R&D stage, that´s why they are not covered in this overview.

Solvolysis

Solvolysis, also referred to as chemolysis or depolymerization, is a process that breaks down plastic fractions into monomers and sometimes oligomers through reactions with solvents. This method is suitable for specific plastics, such as polyesters or polyamides, which can be decomposed chemically by solvents like acidic or alkaline solutions, glycolysis, or alcoholysis. The process requires precise solvents to selectively dissolve bonds, such as ether or ester bonds, without dissolving other plastics, which remain as solid residue. Operating conditions for solvolysis range from room temperature up to approximately 300°C, and pressures range from ambient to 40 bar. After dissolution, the remaining solid material is separated through filtration, and the solution containing monomers is purified before being returned to the polymerization process [8].

Unlike pyrolysis, which can depolymerize all polymers and polymer mixtures, solvolysis is a much more selective recycling process that must be tailored to the specific polymer. For plastic fractions that are largely pure or moderately polluted and cannot be mechanically recycled due to factors like coatings, solvolytic processes are well-suited. These processes effectively break down the plastic into its monomers. After purification, these monomers can be directly reused in polymerization processes. Solvolysis breaks down the polymer into its components gradually, making it suitable almost exclusively for polycondensation polymers that contain heteroatoms like nitrogen or oxygen in the main chain [89].

The primary challenge with these processes is handling plastic waste that often contains significant amounts of impurities, contaminants, and foreign plastics, which result in high solid content in the solution, making filtration and recovery difficult. Additionally, it is essential to ensure that harmful or toxic solvents are not used to avoid environmental contamination [8].

For solvolysis to be effective, the waste polymers must meet certain quality and cleanliness standards. While solvolysis can eliminate additives and foreign polymers, the purification process can become exceedingly intricate and expensive if it requires recovering monomers devoid of numerous unwanted low-molecular-weight components such as co-monomers, degraded monomers, or functional additives like dyes and antioxidants [72].

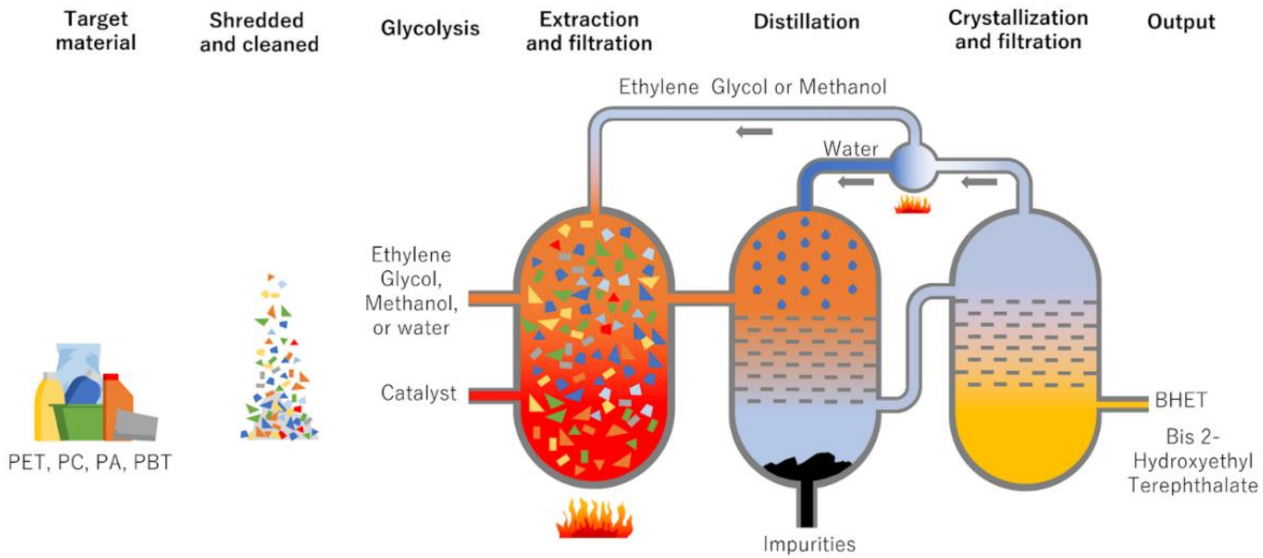


Figure 53. Schematic view of a typical solvolysis process [90]

Solvolytic processes are anticipated to deliver particularly high product quality because the solvents used enable very selective dissolution of the relevant polymer or associated monomers. However, reliable data on this is not yet available. After filtration and purification, the material produced is typically indistinguishable from conventionally obtained feedstocks from the fossil-based supply chain. The process does generate residuals that are unsuitable for material utilization and can result in considerable disposal costs.

The presence of high contents of inorganic solids, foreign plastics, contaminants, and impurities in the feedstock can significantly impede the overall functionality of the process. While these factors may not drastically affect product quality, they can negatively impact the efficiency and operation of the process if they exceed the designated operational limits.

Dissolution-precipitation processes (**discussed in the section on Dissolution and precipitation**) are similar to solvolysis but aim to retain the polymer structures without breaking them into monomers. That´s why Dissolution - Precipation is considered as material recycling and not as a chemical recycling technology. It is summarized together with the mechanical recycling to the group of physical recycling technologies. This distinction is important and might be advantageous in regions where legislation favours physical & mechanical recycling solutions to meet recycling quotas. Both solvolysis and dissolution-precipitation allow for the removal of contaminants, fillers, and foreign plastics from the desired monomers or polymer chains due to the use of specific solvents under moderate conditions.

Technology examples for chemical recycling approaches based on solvolysis are the following:

- CURE Technology: Based in the Netherlands. The company developed an innovative solution for the recycling of Polyester by Solvolysis. A first pilot has been implemented successfully (https://curetechnology.com/)
- IONIQA: Based in the Netherlands. Did develop successfully a solution for the recycling of PET based on Solvolysis (https://ioniqa.com/)

Liquefaction

Liquefaction in an oil bath, also known as depolymerization, differs from solvolysis by causing a more generalized breakdown of plastic fractions. Liquefaction is suitable for recycling mixed thermoplastic fractions. This process occurs at temperatures between 250 and 420 °C under ambient pressure with short residence times and may involve various additives like catalysts or neutralizers. The resulting products are hydrocarbon mixtures, or product oil, containing numerous chemical compounds and impurities from the feedstock. These mixtures require extensive purification, hydrogenation, and possibly distillation to become valuable recycling products. Industrial-scale processes can achieve liquid yields of 70% to 90%, depending on the purity of the input material. The complex purification steps require refinery infrastructure or chemical facilities for further processing of the produced product oil [8].

Given the heterogeneity of plastic waste, extensive purification is necessary to remove heteroatoms such as nitrogen, sulfur, chlorine, and oxygen before the oil can be processed further in the chemical industry or refineries. The solid residue from the process, which contains coke, fillers, aluminum flakes, dust, used additives, and other contaminants, must be treated thermally due to its high organic content and the presence of potentially hazardous components like heavy metals and polyaromatic hydrocarbons (PAH). Additionally, a permanent gas byproduct, which remains gaseous at normal temperatures and pressures and contains burnable and potentially toxic constituents, must also be treated thermally.

Utilizing side products, such as gas and produced waxes, in the downstream production of new polymers, particularly at integrated refinery sites, enhances the overall process efficiency and increases the yield of high-value chemical products (e.g. ethylene, propylene, butene, butadiene, aromatics). Operating such plants on-site and in conjunction with refinery technology is sensible due to the achievable yields of high-quality products. However, the process generates residuals that are unsuitable for material utilization and can lead to significant disposal costs [8].

Technology examples for chemical recycling approaches based on liquefaction are the following:

- Carboliq: German company with a first industrial plant for the recycling of film plastic waste under operation (www.carboliq.com)

Pyrolysis

Pyrolysis has been under exploration by major chemical producers for processing plastic waste for approximately 30 years. Despite achieving technical success, these technologies remained uncommercialized due to their inability to compete with cheap crude oil. The increase in oil prices during the early 2000s prompted startup companies to revisit plastic pyrolysis, leading to the emergence of numerous technology providers today. Recently, oil and chemical giants have also entered this arena, focusing less on developing new pyrolysis technologies and more on plans to utilize the resulting pyrolysis oil in their steam crackers [72].

Pyrolysis is a process that decomposes substances solely through heat, requiring an oxygen-free reactor environment. This thermal treatment breaks down polymers into smaller molecules at temperatures of 400-550 °C and atmospheric or sometimes elevated pressures, under an inert atmosphere to prevent oxidation. Pyrolysis is versatile and can handle varied feedstock consistencies and compositions. Some operators use catalysts to aid the decomposition of plastics.

During pyrolysis, the generated pyrolysis gases are rapidly cooled and condensed to produce desired liquid products, typically resulting in two or more fractions with varying consistencies and viscosities. A permanent combustible gas remains post-condensation, which is usually utilized to heat the process. The remaining solid residue (char), which is of low quality for material use, must be thermally treated in a waste incineration facility.

Higher process temperatures and longer residence times favour the breakdown of long-chain polymers into lighter fractions, such as gases. In contrast, moderate temperatures and shorter residence times promote the formation of heavier oil fractions with longer chain lengths. Due to the relatively low technical complexity of pyrolysis technologies, numerous companies have developed various approaches in recent years. Currently, around 100 different suppliers or developers are active in the market for pyrolytic chemical recycling of plastics [8].

Figure 54 is showing an illustrative process scheme of a typical pyrolysis process.

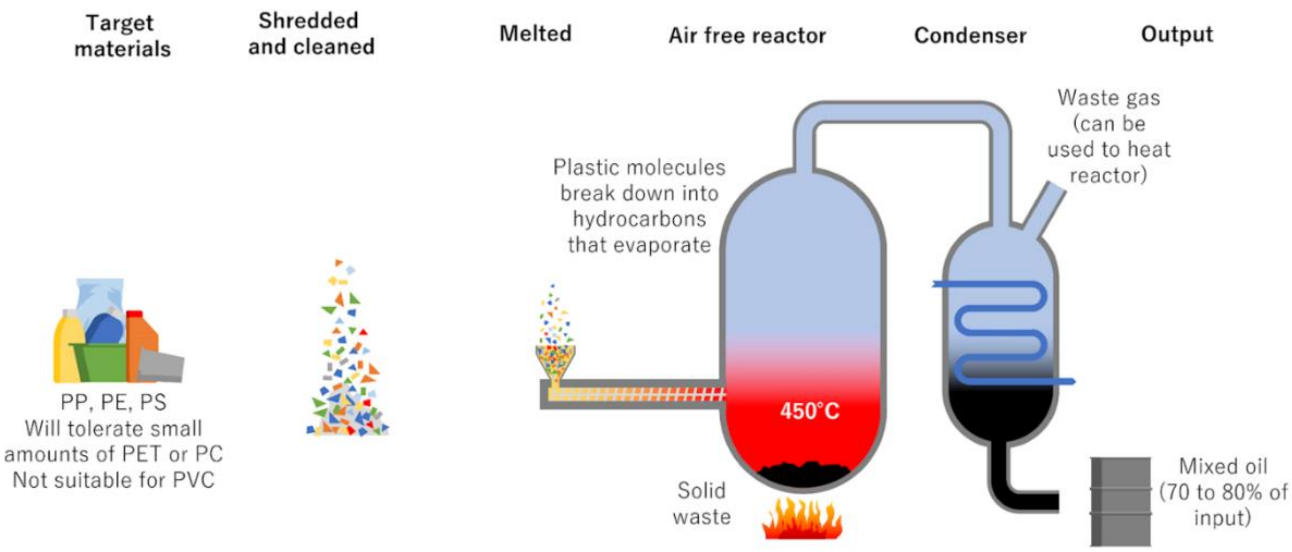


Figure 54. Schematic view of a typical pyrolysis process [90]

Currently, pyrolysis is primarily applied to mixed polyolefins (PE and PP) found in packaging, bags, films, and mixed plastic waste, as well as polystyrene (PS) from insulation and food packaging, and rubber tires. Unlike mechanical recycling, pyrolysis has greater potential to process waste from mixed streams for use in food contact applications [77]. Pyrolysis is not suitable for the recycling of PVC [90]. An important advantage in comparison to gasification of plastic waste is that pyrolysis projects from a technical point of view are simpler and can be installed at a smaller scale and in a modular way.

Technology examples for chemical recycling approaches based on pyrolysis are the following:

- Quantafuel: Norwegian company, which did develop a pyrolysis technology for the recycling of hard to recycle plastic waste. Currently one pilot and one commercial plant in Denmark in operation (https://www.quantafuel.com/)
- Plastic Energy: Headquartered in London. Implementing pyrolysis plants for the recycling of hard to recycle plastic waste. Two commercial plants in Spain operative (https://plasticenergy.com)
- SynCycle: Based in Austria. Did developed a decentralized solution based on pyrolysis for the recycling of mixed plastic waste (https://www.syncycle.com/)

Gasification

Gasification processes aim to produce synthesis gas, primarily composed of hydrogen and carbon monoxide, which can be used to produce basic chemicals after cleaning and upgrading. This method can be seen as an extension of pyrolysis, involving the conversion of pyrolysis products through the controlled addition of reactants like oxygen, water vapour, or carbon dioxide. The solid and gaseous products from the drying and pyrolysis of plastic waste are further transformed via homogeneous (gas-gas) and heterogeneous (gas-solid) reactions. In situations involving highly heterogeneous and contaminated plastics, which may include toxic components, gasification stands as the sole traditional thermochemical method capable of producing usable materials, specifically synthesis gas.

There are two operational modes of gasification depending on the gasification agent used: autothermal and allothermal. Autothermal gasification involves the presence of sufficient oxygen, leading to partial oxidation of the components, generating heat through exothermic reactions, and eliminating the need for external heating. In contrast, allothermal gasification, which uses water steam or CO_2, requires external energy since it involves no exothermic reactions.

The synthesis gas produced by gasification mainly consists of hydrogen and carbon monoxide, but also contains methane, aliphatic and aromatic hydrocarbons, and other components. However, the production of gas from solid fuels presents significant challenges, particularly due to high tar content, which can condense in pipes and process equipment, affecting downstream components. These issues are exacerbated by waste-derived feedstocks of lower quality. These observations underscore the significant contamination of product gases from plastic gasification with tars. This contamination presents a major challenge for further utilization and necessitates substantial multi-stage cleaning efforts, which consume considerable energy and generate residual materials.

Due to the high costs of building and operating gasification plants and the need for large-scale facilities for economic viability, the number of chemical recycling processes based on gasification is limited [8].

Figure 55 below is showing an illustrative process scheme of a typical gasification process.

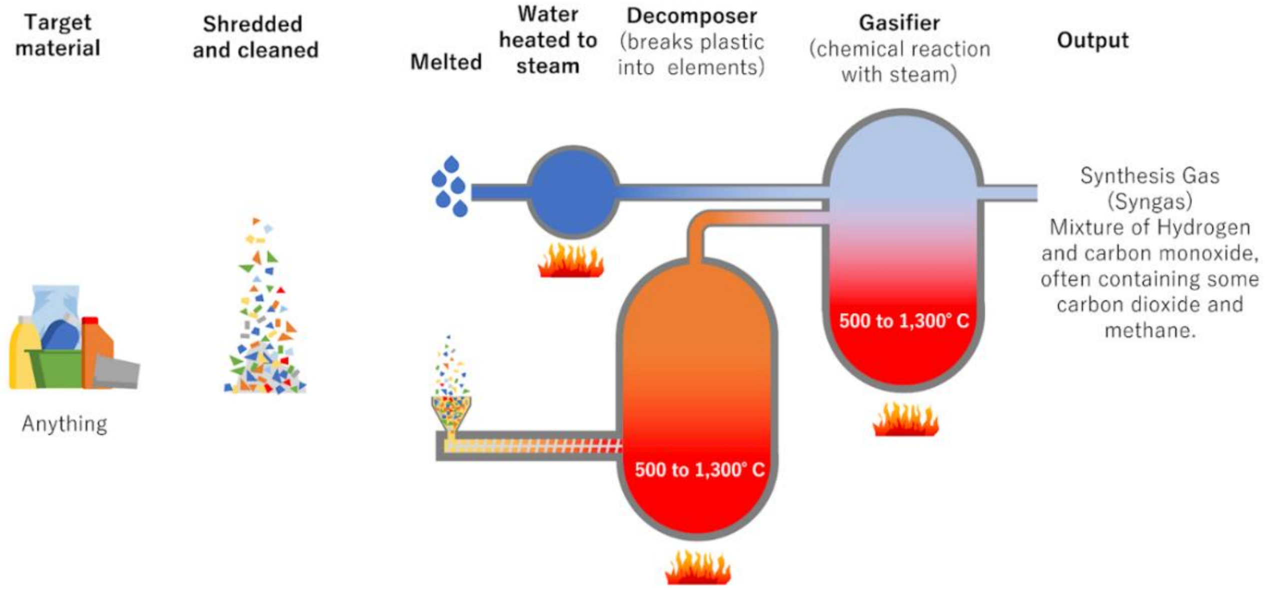


Figure 55. Schematic view of a typical gasification process [90]

<u>Technology examples for chemical recycling approaches based on gasification are the following:</u>

- ENERKEM: Canadian company, which is offering a solution for the recycling of mixed plastic waste based on gasification (https://enerkem.com/)

Upcycling of plastic waste through chemical recycling

Sometimes specific chemical recycling technologies are marketed as upcycling of plastics waste. In principle these processes involve chemical recycling plus additional process steps focusing on refining the product resulting from the chemical recycling.

Utilization of thermoplastic waste in the production of fuel

The utilization of thermoplastic waste in the production of fuel offers a promising solution for managing plastic waste and addressing energy needs, particularly in remote regions. Through processes such as pyrolysis, thermoplastic waste can be converted into liquid fuels that can replace conventional diesel and other petroleum products. This approach not only provides a valuable use for plastic waste but also helps reduce dependence on fossil fuels, contributing to energy security and sustainability.

However, several challenges and environmental issues must be considered. The conversion process requires significant energy input and therefore is resulting in resource losses. Additionally, the quality and consistency of the produced fuel can vary, necessitating further refinement to meet industry standards. There are also potential health risks associated with the handling and processing of plastic waste, including exposure to harmful chemicals and pollutants. Moreover, this approach does not contribute to a circular economy, as the plastic waste is ultimately burned and therefore lost for further uses. This leads to high greenhouse gas emissions. Despite these challenges, the production of fuel from thermoplastic waste represents a viable interim solution for waste management and energy generation, particularly in areas with limited access to conventional fuels or where fuels are expensive. For example, on remote islands or isolated regions.

Technology examples for chemical recycling used for fuel production are the following:

- HVO Swiss: Based in Switzerland. Selling a decentralized solution for the recycling of mixed plastic waste for the production of drop-in fuel for replacing Diesel (www.hvoswiss.ch/)
- Environment Energy Co: Japanese company which developed a solution for recycling of plastic waste to replace diesel (www.environment-energy.co.jp/)

Upcycling plastic waste to hydrogen

The upcycling of plastic waste to produce hydrogen is an innovative approach that addresses plastic pollution while contributing to the energy sector. This process utilizes thermochemical methods such as pyrolysis or gasification, where plastic waste is heated in the absence of oxygen to produce syngas, which can then be processed to extract hydrogen. Although this technology shows significant promise, it is still in the experimental and early commercial stages. A primary drawback is the high energy input required for the conversion process, which can diminish some of the environmental advantages. Additionally, managing by-products and ensuring the purity of the produced hydrogen are substantial challenges. Despite these issues, the potential for this technology is considerable, as it offers a way to repurpose plastic waste effectively. With further advancements in efficiency and scalability, upcycling plastic waste to hydrogen could become an essential part of sustainable waste management and energy strategies, although it must be noted that this hydrogen is still fossil-based and not a fully clean energy source [91].

Strengths of chemical recycling

Chemical recycling technologies are seen as promising ways how to deal with hard to recycle plastic waste by currently prevailing mechanical recycling solutions. The following points are summarizing these benefits, which have to be seen also critical because of the often not yet commercial availability of these chemical recycling solutions on a larger scale.

Chemical recycling provides a means to recycle plastic waste that cannot be processed through traditional mechanical recycling. The primary goal is to reintroduce the carbon, specifically hydrocarbons, from non-materially recyclable plastic waste back into the production cycle. This method is applicable to waste fractions of various quality levels and compositions.

- Versatility of output products: Chemical recycling processes can convert plastic waste into a variety of valuable outputs, including chemicals, oils, and synthesis gas. These products have diverse applications, such as in the production of new plastics, fuels, and other chemical materials, making chemical recycling adaptable to multiple industries.
- Handling a broad range of plastics: Chemical recycling is capable of processing a wide range of plastic waste types, including those unsuitable for mechanical recycling due to contamination or complex additives. For relatively pure and moderately contaminated plastic fractions, solvolytic processes can break down plastics into monomers, which can then be reused in polymer production.
- Removal of contaminants: Chemical recycling allows for the removal of contaminants, such as additives and dyes, that are typically embedded in plastic waste. This capability is particularly important for producing high-purity recycled plastics, a task that mechanical recycling cannot achieve, making chemical recycling more effective for certain waste streams.
- Processing mixed thermoplastic fractions: Mixed thermoplastic fractions, which present challenges for mechanical recycling, can be treated through liquefaction or pyrolysis. These processes produce an oil that, after upgrading, can be utilized in refineries or chemical facilities, enabling the conversion of complex plastic waste into usable materials.
- Managing highly contaminated plastics: For highly heterogeneous and contaminated plastics, including those with toxic components, gasification is a chemical recycling method that generates synthesis gas. This gas can then be used as a feedstock for chemical production or energy generation, making it possible to recycle even the most contaminated plastic waste.

- Infinite recycling potential: Chemical recycling processes, such as solvolysis and pyrolysis, offer the potential for repeated recycling of the same plastic material without degradation. This capability can significantly reduce the need for virgin fossil resources, supporting ongoing material use within a circular economy.
- Contribution to Circular Economy: Chemical recycling facilitates the recycling of plastics that are typically difficult to process mechanically, thus preventing them from being incinerated or landfilled. This process reintroduces valuable resources into the production cycle, aligning with the principles of a circular economy.

Limitations of chemical recycling

Chemical recycling faces several limitations. Firstly, some of the chemical recycling technologies, e.g. Pyrolysis and Gasification have a high energy intensity, what makes the process economically challenging. Chemical Recycling is also heavily reliant on demand for recycled feedstocks, e.g. from local petro-chemical industries, refineries, etc., where the recycled base materials can be incorporated in existing production facilities. Another issue is the variability in production yields and potential co-products, such as fuels. Additionally, chemical recycling plants require a stable and continuous supply of feedstock in large quantities to remain economically viable. The technological set-up in general is designed for a certain type of feedstock. Variations in the feedstock supply might provoke operational issues with direct impact on its profitability and might change the quality of the output products [77]. Chemical recycling plants are very complex installations that require extensive safety precautions. Usually, these plants require economies of scale and thereby very high investment cost.

Although individual chemical recycling processes have been operational for years, chemical recycling of plastics as a whole cannot yet be considered state-of-the-art technology. Practical issues frequently arise, especially when dealing with contaminated input material. As a result, many efforts to implement these processes fail during the development stage or commissioning [8].

Reliable data on the economic viability of processes for chemical recycling of plastic wastes are scarce. Information provided by companies should be approached with caution, as it often sets optimistic conditions and tends to overlook the economic challenges associated with implementing innovative technologies that require demanding input materials. Despite the current favorable political and public acceptance of ecological and resource-efficient initiatives, several companies in the chemical plastic recycling sector have recently filed for insolvency. Promising concepts that received positive feedback in laboratory and pilot plant settings have evidently struggled in scaling up to industrial operations due to economic challenges in practical application [8].

In regions with strong governmental oversight of plants and emissions and advanced waste management systems, chemical recycling plants do not pose a greater environmental risk than other waste treatment or thermal processing plants. Authorities enforce strict emission limits and waste treatment standards from the authorization process through the entire plant lifecycle, ensuring compliance and continuous monitoring. Therefore, operating chemical recycling plants in areas with stringent environmental regulations (e.g., Europe, North America, Japan, or Australia) is no more environmentally harmful than running similar industrial plants.

Conversely, in countries lacking proper infrastructure and monitoring, the situation is fundamentally different. Without effective official control, there is little incentive for investments in environmental and health protection. Chemical recycling processes involve handling potentially hazardous substances, including additives, solvents, by-products, and residual materials. Inadequate safety measures in such settings inevitably pose risks to human health and the environment. Thus, in regions with insufficient or unregulated waste management, installing chemical recycling processes, especially on a small scale, should be approached with caution.

Complementarity between mechanical and chemical recycling

Mechanical recycling is still the state-of-the-art solution which is applied for almost all plastic recycling projects implemented on an industrial scale globally. This can easily be seen in Figure 3 and Figure 4. Due to its limitations for the recycling of unsorted and contaminated plastic waste streams worldwide alternative recycling solutions are investigated with the aim to find for hard to recycle plastic streams technical solutions for its recycling. These alternative recycling technologies are commonly summarized under the term chemical recycling, advanced recycling, or molecular recycling solutions. This also means that the aim should not be to replace mechanical recycling, which has been proven to be successful and cost effective, but to complement it with new technologies, which are able to process plastic waste streams, which are unsuitable for mechanical recycling and are currently landfilled or incinerated.

Despite its potential, chemical recycling is still in its infancy and rarely exists on a commercial scale. It faces numerous challenges, including high operational costs, significant energy requirements, and more complex technological processes. The scalability of chemical recycling is also a major concern, as many of the existing pilot projects have yet to prove economic viability on a large scale. Additionally, chemical recycling can generate by-products and emissions that need careful management, raising environmental concerns.

Mechanical recycling is highly effective for clean, homogeneous plastic waste, turning it into new products with relative ease. However, when dealing with contaminated, mixed, or multi-layered plastics, mechanical recycling struggles to maintain material quality and economic viability. Chemical recycling can theoretically address these issues by breaking down complex plastic waste into basic chemical components, which can then be reused to create new plastics or other valuable products. However, the reality is that many chemical recycling processes are still experimental and have not yet demonstrated consistent success outside of controlled environments.

The idea of complementing mechanical recycling with chemical recycling is promising, but it requires significant advancements in technology, infrastructure, and regulatory support to become a practical reality. Current chemical recycling methods must overcome hurdles related to efficiency, environmental impact, and cost. Furthermore, the integration of these two recycling methods would necessitate a well-coordinated waste management system to direct appropriate waste streams to the correct recycling processes.

Recycling projects must be seamlessly integrated into the broader waste management and economic (industrial) system of a given location. Successful implementation hinges on two critical factors. First, there must be a consistent and adequate supply of suitable plastic fractions tailored to the specific recycling technology employed. This necessitates an efficient collection, sorting, and pre-processing infrastructure to ensure a steady stream of suitable input materials. Second, the local demand for the output products is crucial. The recycled materials must meet the quality and quantity requirements of local industries, ensuring that they can be absorbed into the production processes as feedstock for further manufacturing steps. Furthermore, the presence of an industrial processing infrastructure is essential for adding value to the recycled products. This integration not only supports the economic viability of the recycling projects but also enhances their environmental benefits by reducing transportation emissions and promoting local economic development. Additionally, fostering collaborations between recycling facilities, local industries, and policymakers can help create a robust circular economy, driving innovation and sustainability in the region. By addressing these interconnected elements, recycling initiatives can achieve greater efficiency, economic feasibility, and environmental impact. Ultimately, while chemical recycling holds potential as a supplement to mechanical recycling, its current limitations mean that it is not yet a viable large-scale solution. The complementary approach to plastic recycling will require continued research, development, and investment to address these challenges and realize the full potential of both methods.

Concluding chemical recycling is an important approach to target plastic waste fractions that cannot be recycled mechanically in order to increase the overall recycling rate.

Biological recycling

Biological recycling, or also called bio-recycling, has been under investigation in the last couples of years mainly by university and research organization and is still in a very early stage of development. It involves microbial and enzymatic degradation processes, followed by the chemical or biological conversion of degraded polymers into monomers or other valuable chemicals. Enzymatic reactions enable the breakdown of long plastic polymers into monomers without requiring high temperatures or chemical catalysts, and without compromising product quality. This bio-recycling method supports sustainable, economically feasible, and potentially endless recycling of synthetic polymers.

The effectiveness of biodegradation is influenced by the organisms and enzymes used, the inherent properties of the polymers, and the pre-treatment methods applied to the plastics. Biodegradation refers to the breakdown of organic substances by biological entities, such as microorganisms (bacteria, fungi, and marine microalgae) or enzymes. This process typically occurs after or alongside abiotic degradation. While synthetic polymers were initially thought to be resistant to microbial degradation, recent research has shown that some microbes have evolved to produce hydrolytic enzymes capable of degrading these polymers [92].

Biodegradation of polymers by microorganisms involves several steps. Initially, the macrostructure of the plastic matrix is fragmented into smaller pieces due to abiotic and biotic factors such as solar light, irradiation, oxygen, pH, moisture, temperature, pressure, and abrasion. Microorganisms that can use plastics as a carbon source and energy source, attach to the polymers, leading to surface colonization and biofilm formation. Biofilm communities growing on and inside the plastics cause biodeterioration, enlarging pore sizes and facilitating cracks. Biofragmentation is driven by extracellular polymer-degrading enzymes (e.g. oxygenases, ureases, esterases, lipases, proteases, depolymerases, cutinases) secreted by microbial colonies. These enzymes lower the molecular weight and shorten the carbon-chain backbone of polymers by depolymerizing them into oligomers, dimers, and monomers, which can then be assimilated by the microorganisms. The final step of polymer biodegradation is mineralization, where completely oxidized metabolites such as CO_2, CH_4, N_2, and H_2O are excreted [93].

However, several challenges still hinder large-scale bio-recycling of PET and other plastic wastes. The diverse physical properties of PET significantly affect biodegradation efficiency, necessitating further research to develop more efficient processes. PET is hydrophobic, non-polar, chemically inert, and has poor surface wettability, making it difficult to bond and coat. Since polymer biodegradation is a surface process, the adsorption of enzymes onto the plastic surface is crucial and needs to be optimized for improved degradation.

The second significant challenge is the variability in process conditions and pretreatment needs caused by differences in PET waste sources. PET wastes from diverse applications often possess varying impurities and physical characteristics, such as shape, crystallinity, glass transition temperature, and mechanical strength. These variations can result in markedly different biodegradation efficiencies under identical process and reaction conditions, complicating the establishment of standardized and effective bio-recycling methods [93].

The third major challenge is the insufficient knowledge and experience in scaling up current biodegradation technology. Research on reaction engineering and reactor design, focusing on critical factors and parameters for the scale-up process, is still sparse. This gap hinders the development of effective large-scale biodegradation systems for PET and other plastic wastes [93].

Enzymatic bio-recycling of plastics presents several challenges that must be addressed for its widespread adoption.

- The process tends to be more costly than producing new plastics, and companies may face substantial initial expenses when setting up bio-recycling facilities.
- The enzymes currently identified by researchers can only degrade a limited number of plastic types, which restricts the range of plastics that can be effectively recycled through this method.
- There are significant knowledge gaps regarding the potential unintended consequences of bio-recycling. For instance, more research is needed to understand the environmental risks associated with engineered enzymes if they are released into the environment.

Overcoming these challenges through further research, technological advancements, and regulatory frameworks will be essential to harnessing the full potential of enzymatic bio-recycling as a sustainable solution for managing plastic waste.

On the other hand, bio-recycling offers a couple of interesting opportunities. Economic, environmental, and health benefits can be substantial. By converting plastic waste into valuable products, bio-recycling supports a circular economy and reduces reliance on fossil fuels for new plastics. Additionally, these methods can mitigate the health risks associated with incinerating plastic waste.

Bio-recycling also enhances processing efficiency. Unlike mechanical recycling, it requires less stringent sorting of plastic waste, saving both time and money. Moreover, it consumes less energy compared to mechanical and certain chemical recycling processes.

These advantages underscore the potential of enzymatic bio-recycling to transform plastic waste management into a more sustainable and economically viable practice [94].

Technology examples for biological recycling are the following:

- Carbios: French company which did develop a proven plastic recycling solution based on enzymes. (https://www.carbios.com/en/)
- Samsara Eco: Australian company which is developing a solution for plastic recycling by using enzymes (www.samsaraeco.com)
- Protein Evolution: Developing a solution with AI-designed enzymes for the recycling of Polyester plastic waste (www.protein-evolution.com)
- TEX2MAT: Research project financed by the Austrian Research Agency FFG for the recycling of plastic waste via Enzymes: (https://projekte.ffg.at/projekt/2937574)

Plastic recycling technologies and their environmental and climate change mitigation impact

To ensure a circular economy for plastics, it is essential to understand the environmental impacts of recycling and make optimal recycling choices for specific plastic polymers.

Efficient recycling of spent polymers should not only focus on effectively recycling the carbon but also on minimizing energy consumption and waste production throughout the product's life cycle. This generally means operating through the smallest possible recycle loop. Depending on the quality and purity of the waste, the priority should be given to reuse first, followed by reprocessing (mechanical recycling), depolymerization to the monomer, conversion to hydrocarbon feedstock, and finally, as a last resort, energy recovery. This priority list, in accordance with the waste hierarchy, which is used in the waste management sector for prioritizing treatment solutions for waste, aims to maximize the value of the recycled product while minimizing energy and material waste throughout the entire cycle. This principle is illustrated in Figure 56 below.

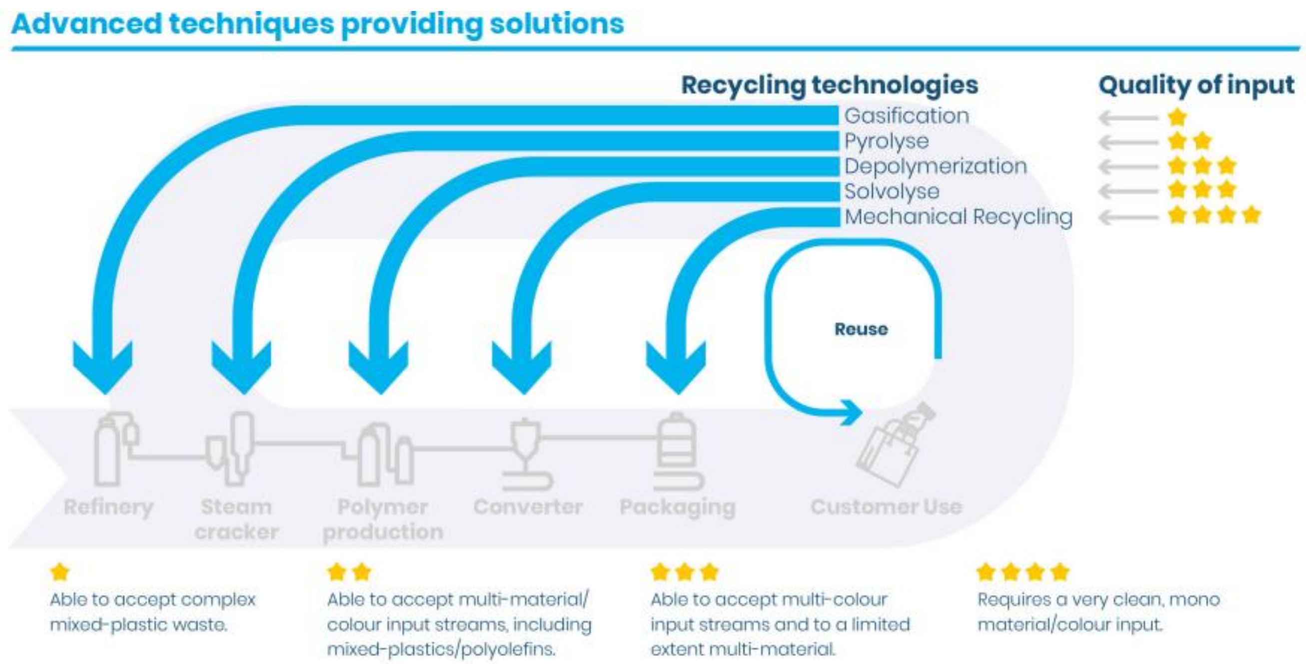


Figure 56. Overview of different loops for plastics in a circular economy [71]

In line with circular economy principles, "inner loops" or “shorter loops” are more efficient at preserving value by avoiding the economic and environmental costs of breaking down and rebuilding material structures. Among the various recycling processes, mechanical recycling is closest to the "innermost" loop, while chemical recycling is considered an "outer loop" because it involves more extensive breakdown of materials.

With regard to the necessary quality of the input streams used from the plastic waste that is recycled, it can generally be stated that the closer to the usable final plastic product the output product stream from the recycling process is fed into the plastic value chain (inner loops) the higher the quality has to be. E.g. for mechanical recycling the waste separation and pre-processing steps are much more demanding than for pyrolysis or gasification plants in order to supply the recycling process with input plastic waste [71]. However, it should be clearly stated that this only is true if the chemical recycling plant actually is capable of coping with such a quality of plastic waste. In reality often times chemical recycling plants ask for input specifications that are similar to those for mechanical recycling.

In practice the assessment which recycling option is the most environmentally friendly is much more complex and depends on a multitude of factors like type of plastic, specific recycling process and its process parameters, local market conditions and the type of resource, which is replaced by the recycled plastic, and many more. Therefore, for each concrete plastic recycling project essentially only a specific Life-Cycle-Assessment allows to get concrete information about its environmental performance.

An interesting investigation in this regard has been conducted by the German Chemical Society [95] where different End of Life (EoL) scenarios for plastic waste have been compared in order to compare their GHG emissions during their life cycle. In this case incineration without energy recovery, Incineration with energy recovery, Landfilling, Pyrolysis, mechanical recycling, Solvolysis and dissolution/precipitation have been compared for different plastic types. It is important to highlight that the outcome of this study is just applicable to the German setting because such Life-Cycle-Assessments are always a matter of alternatives, what is highly dependent on the local context. The results of this study are shown in Figure 57 and discussed in the following paragraph.

When plastic is incinerated, 5 to 10 tonnes of CO_2 are released for every tonne of plastic throughout its life cycle. This variation is due to differences in carbon content, production energy requirements, and the types of plastic involved. About half of these emissions come from plastic production, while less than a third arise from carbon released during incineration. The remaining emissions are related to the final product assembly, with minimal emissions from waste transport. Energy recovery from incineration can avoid 30 - 45% of CO_2 emissions compared to traditional electricity generation (depending on local electricity grid).

Alternative treatments to incineration, which avoid the need for new resource production, reduce end-of-life CO_2 emissions. Landfilling results in CO_2 emissions that are about one-third of those from incineration without energy recovery, as the embodied carbon is rarely released. However, landfilling is not a circular solution and can cause soil and groundwater contamination without costly preventative measures.

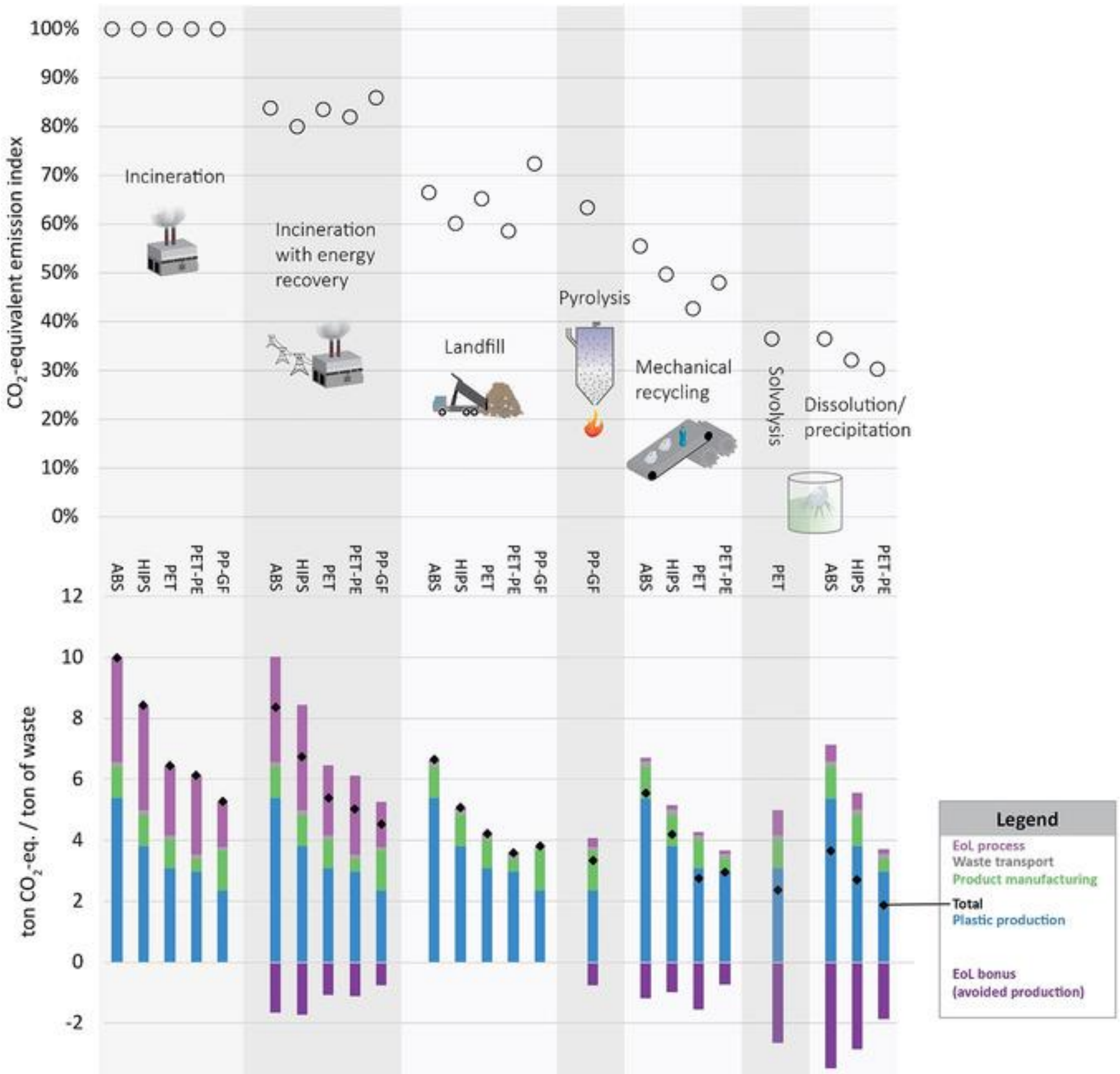

CO2-equivalent emission index
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Incineration
Incineration with energy recovery
Landfill
Pyrolysis
Mechanical recycling
Solvolysis
Dissolution/ precipitation
ABS
HIPS
PET
PET-PE
PP-GF
ton CO2-eq. / ton of waste
12
10
8
6
4
2
0
-2
Legend
EoL process
Waste transport
Product manufacturing
Total
Plastic production
EoL bonus (avoided production)

Figure 57. CO_2-equivalent emissions of different EoL treatment technologies applied for several plastic-waste streams [95]

Dissolution/precipitation processes save the most CO_2 (65-75%) since they avoid breaking and reforming bonds. Solvolysis also offers significant CO_2 savings by efficiently converting uncontaminated PET waste into high value recyclate. Pyrolysis can replace fuel oil and natural gas, avoiding 30% of the CO_2 emissions of incineration. Mechanical recycling of mixed plastics saves around 25% of CO_2 emissions due to the lower quality of recyclate.

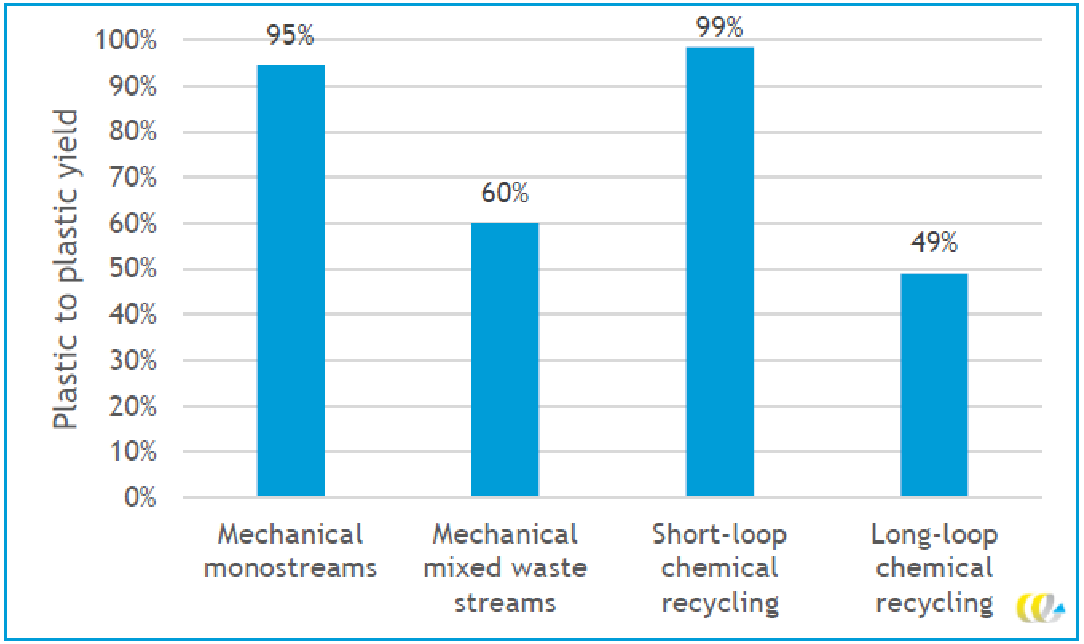
CO_2 savings are achieved mainly through avoided production, pyrolysis oil, or energy production. Reuse is preferable to all recycling routes since recycled products still need to be remanufactured and transported. Electrification of these processes via renewable energy could further reduce emissions but is not directly related to recycling. Future polymer production may use sustainable monomer sources, such as CO_2-derived methanol, to reduce emissions further.

While this analysis highlights the benefits of certain end-of-life technologies, it needs to be extended to more plastic waste streams and emerging chemical recycling technologies. The key finding is that the less the polymer structure is broken down and the higher the quality of the recycled product, the better the environmental performance [95].

The P2P yields of plastic recycling techniques

To achieve high recycling rates and maximize environmental benefits, plastic waste must be processed optimally, minimizing sorting and separation losses while ensuring a high plastic-to-plastic (P2P) yield. The P2P yield measures the amount of new plastic that can be produced from recycled plastic waste, expressed as a weight share. This yield, along with sorting and separation yields, indicates the efficiency of transforming plastic waste into recyclate. This necessitates selecting the appropriate combination of plastic recycling techniques, as the composition of these techniques significantly impacts the environmental effectiveness of plastic recycling. Different recycling methods yield varying P2P efficiencies, thus influencing the overall environmental impact. Therefore, careful consideration and selection of recycling techniques are crucial to enhance the sustainability and efficacy of plastic recycling processes [96].

In an interesting study by CE Delft the P2P yield of different plastic recycling scenarios have been compared. In this analysis is mechanical recycling (mono-stream plastic waste and mixed plastic waste) has been compared with short-loop and long-loop chemical recycling technologies. A short-loop chemical recycling technology is for example solvolysis, which allow to feed the output product of the recycling process (monomers) close to the final plastic product into the plastic value chain. Long-loop ("outer loop") recycling technologies are for example pyrolysis and gasification, where the output product needs further processing, like cracking and repeated polymerization. The results are shown in Figure 58 below.



* Figures for gasification are excluded, because these figures are uncertain. Therefore, the P2P yield of long-loop chemical recycling is based on the P2P yield of pyrolysis, which is 49%.

Figure 58. P2P yield of different plastic recycling technologies [96]

The P2P yield for mechanical recycling varies from 60% for mixed plastics to 95% for single materials. Short-loop chemical recycling has a P2P yield of around 99%. In contrast, long-loop chemical recycling has lower yields, with 34% for gasification and 49% for pyrolysis, though gasification figures are uncertain. Therefore, long-loop chemical recycling requires more plastic waste to produce 1 kg of recyclate compared to mechanical and short-loop chemical recycling.

Despite its lower P2P yield, long-loop chemical recycling can be beneficial in certain situations. It can process plastic waste that mechanical recycling cannot handle, although pyrolysis has stringent requirements, such as limits on polyvinyl chloride content. Additionally, long-loop chemical recycling can produce high-quality recyclate, comparable to virgin plastic, suitable for applications with strict standards, such as food packaging.

While long-loop chemical recycling is beneficial for waste that cannot be recycled mechanically or through short-loop chemical processes, it is environmentally undesirable for it to dominate and purchase waste that could be recycled more efficiently by other methods. Mechanical and short-loop chemical recycling are more effective in converting plastic waste into recyclate, making them the environmentally preferable options [96].

Maturity of recycling technologies

The landscape of plastic recycling technologies is rapidly evolving as research and development efforts intensify to tackle the pervasive plastic pollution problem. New advancements range from improved mechanical recycling methods to innovative chemical recycling techniques that break down plastics into their fundamental components for reuse. Emerging technologies, such as enzymatic recycling and advanced sorting systems using artificial intelligence, promise higher efficiency and broader applicability. However, the maturity of these technologies varies significantly. While some, like enhanced mechanical recycling, are already in commercial use, others, such as chemical recycling, are still in the experimental or early commercial stages. Figure 59 below is summarizing for mechanical and chemical recycling (Purification, Depolymerization and Conversion) technologies the commercial maturity for different plastic types. As easily can be seen, just the mechanical recycling can be considered as commercially mature for several types of plastic wastes.

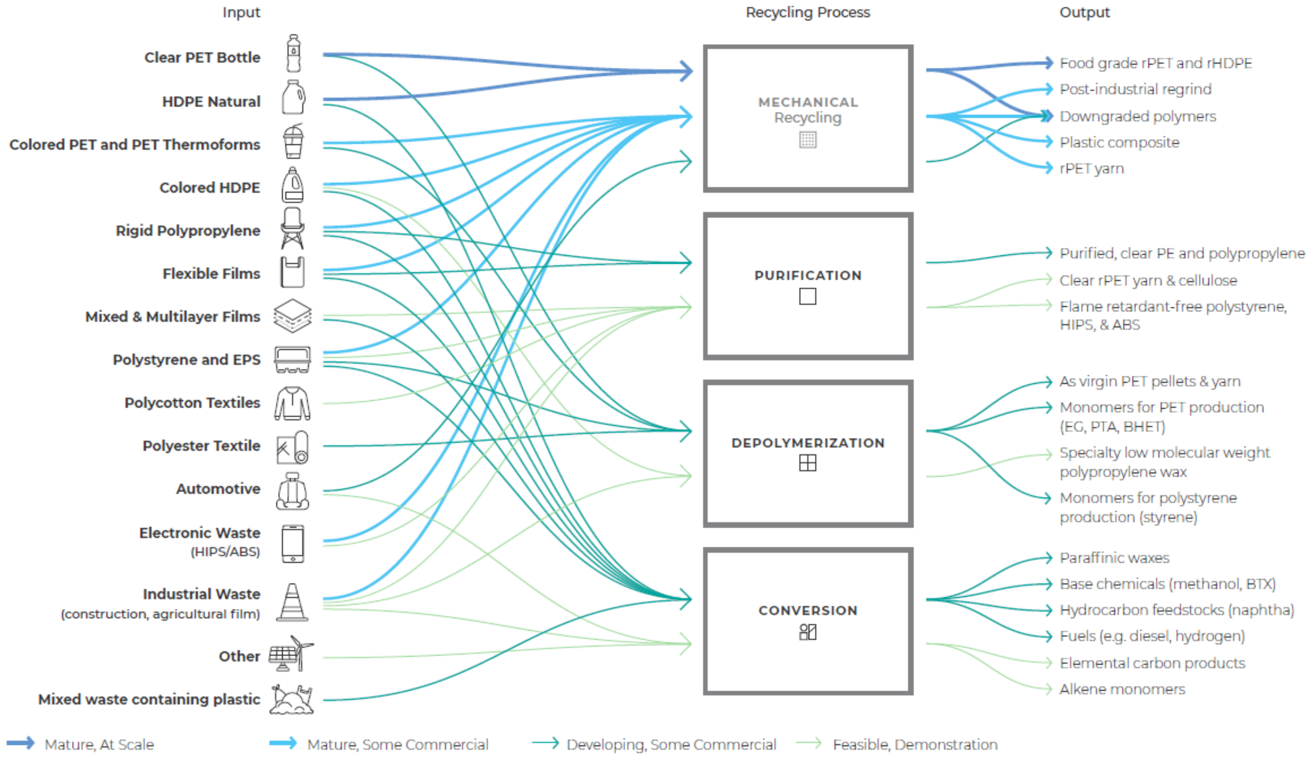


Figure 59. Recycling inputs and outputs early and developing material flows by technology category - maturity of recycling technologies [4]

Case studies

In the following sub-chapters selected case studies are being described in more detail. The focus here is being laid on technological approaches that are either developed and implemented in the Global South or are developed in the Global North aiming at implementation in the Global South.

Bangladesh

In Bangladesh, recycling plastic is not common, and only a small part of the plastics industry uses advanced recycling equipment like shredders or extruders. The process is labour-intensive, with tasks like collecting, sorting and cleaning, done manually due to low labour costs. The setting is therefore to be classified as described in the section on **Mechanical recycling – social inclusion approach**. Workers might earn around 200 BDT ($2) per day. The recycling process involves several stages [97]:

- **Sorting**: Plastic waste is sorted manually.
- **Cleaning**: The sorted plastic is cleaned by hand using surfactants, liquids, and disinfectants to remove pollution such as soil, stains, or oil. The cleaned plastics are often dried in the sun after being washed in a river or pond.
- **Shredding**: The cleaned and sorted plastic waste is cut into flakes using locally made shredder equipment.
- **Extruding**: The plastic flakes are melted in an extruder and then forced through a tiny die-hole to form pellets. These pellets are then used to create new plastic products by pouring into moulds or extruding.

Because Bangladesh produces a lot of plastic waste, recycling is a significant challenge. Bangladesh's recycled plastic sector has the potential to be among the most lucrative. In several parts of Bangladesh, traditional methods of recycling solid waste have been noted; daily, a substantial quantity of plastic, tin, paper, and metal are recycled. Nonetheless, the public needs to be better informed about the issues surrounding the use and disposal of plastics. In Bangladesh, plastic pollution — including microplastics — poses a severe environmental and public health risk. Bangladesh's current system for managing plastic waste lacks sophisticated and technological techniques. By implementing a sustainable plastic management system, Bangladesh can produce energy from garbage and manage plastic waste more effectively.

Entrepreneurs in Bangladesh face challenges in producing and promoting alternatives to single-use plastics due to their hazardous environmental impact. Efforts to develop the recycled plastic business require cooperation among the government, consumers, recycling companies, and plastic product producers. Potential solutions to plastic waste issues include developing plastic substitutes and implementing efficient waste management systems. Favourable consumer behaviour changes and significant market potential are encouraging entrepreneurs to manufacture and promote plastic alternatives.

India - Mechanical recycling: Plastic boards and other products (Trashcon)

The development of Trashbot began in 2016 and the entrepreneur developed a semi-automatic waste segregator. At first it was a small prototype that eventually led to the creation of Trashbot, which has since evolved into a scalable solution with multiple models available for different capacities.

The initial prototype had a processing capacity of 1 kg waste per hour. They then scaled the model up to a 50-kg-per-hour system and later to a 250-kg per hour system. Currently the Trashbot is available in four capacities: 500 kg, 2 tonnes, 5 tonnes, and 10 tonnes per hour.

Figure 60. Plant set-up of TrashBot – automated mixed municipal waste segregation system [98]

The feedstock for the Trashbot technology includes mixed waste from various sources. This mixed waste typically consists of a combination of biodegradable and non-biodegradable materials, including:

- Biodegradable Waste: Organic waste such as food scraps, soiled materials (e.g., plastic-laden sambar), and other decomposable items.

- Non-Biodegradable Waste: Plastics (including single-use plastics), polymers, multilayered plastics, aluminium foils, and other non-recyclable components.

The waste feedstock can also include heavily mixed items, such as diapers, contaminated plastics, and even unexpected items like dead animals or boulders, which the system is designed to handle. The technology is specifically designed to segregate this highly mixed waste efficiently.

Efficiency: The Trashbot can segregate waste with more than 90% efficiency at any given time, processing mixed waste within minutes. The technology separates biodegradable waste (high moisture content) from non-biodegradable waste (lower moisture content) using shredding and air pressure systems.

Processing: The waste is shredded to reduce the surface area where organic waste can stick, and then it passes through a high-pressure fan to separate biodegradables from non-biodegradables.

Outputs and products include biodegradable waste used for generating biogas or producing organic compost/manure. Non-Biodegradable waste is recycled into boards that can be used to make furniture, roofing tiles, partition walls, etc. These boards are termite-resistant, water-resistant, and resemble marble in appearance.

The following business models are used by Trashcon.

- Direct Sale and Use: Customers use the segregator for their waste and manage the outputs (biodegradables and non-biodegradables) themselves.
- Buy-Back Model: Trashcon sells the segregator and buys back the non-biodegradable waste to produce recycled boards, allowing customers to generate revenue.
- End-to-End Zero Waste Management: Trashcon sets up a complete system for zero waste management, converting all outputs into useful products like manure and recyclable boards.

The costs and financials of the operation is as follows. The starting price for Trashbot is Rs. 9 lakh (USD 10,500). The cost varies depending on the capacity. The sale of recycled boards made from non-biodegradable waste is seen as a potential source of significant revenue, with possibilities of generating millions of dollars per month. The company has already established a market for these products in India, as well as internationally in Canada, Australia, and the USA.

- **Social Impact:** The technology has transformed manual waste segregation jobs into more dignified supervisory roles for workers, particularly women who previously had to separate waste by hand.
- **Environmental Impact:** By preventing waste from entering landfills, each tonne of waste processed impacts approximately 4,000 lives (based on the calculation of 1 kg per household of four). https://trashcon.in/

India – Mechanical recycling: Plastic boards and other products (Bamboo House India)

Bamboo House India, based in Hyderabad, is a pioneering Social Business Enterprise (SBE) that merges sustainability with innovation to address pressing environmental concerns, particularly plastic waste. Founded in 2006 by first-generation entrepreneurs Prashant Lingam and Aruna Kappagantula, the enterprise was born out of a need for eco-friendly furniture and has since evolved into a multifaceted organization that supports rural and tribal artisans by utilizing bamboo and recycled plastic waste as versatile, eco-friendly building resources.

India is the world's second-largest producer of bamboo, yet many rural artisans, despite their exceptional craftsmanship, earn meager incomes due to limited market access. Bamboo House India seeks to bridge this gap by providing livelihood opportunities to these artisans while promoting bamboo as a sustainable building material in urban markets. The enterprise also extends its environmental efforts by recycling plastic waste, tire waste, banana fiber, agricultural waste, textile waste, cane, water hyacinth, and other materials, thereby contributing to the green and circular economy.

Bamboo House India's approach includes also the production of a wide range of utility products from recycled plastic, including mobile phone cases, USB sticks, flowerpots, furniture, and more. The enterprise's model is particularly suited for urban local bodies (ULBs), women-led enterprises, self-help groups (SHGs), startups, educational institutions, NGOs, and small-scale units, offering a sustainable solution with a low investment need.

In addition to these innovations, Bamboo House India also produces plastic sheets for houses and shelters, applying down-cycling techniques to transform plastic waste into products.

Uganda – Mechanical recycling: Roof tiles, fence posts and other products (EcoBrix)

Eco Brixs is a closed-loop recycling initiative that addresses the dual challenges of plastic waste and unemployment in Uganda. Established in 2017 in Masaka, Uganda, the organization began by collecting plastic waste in a backyard and has since grown into one of the largest recycling facilities outside the capital, Kampala. The model is community-driven, with over 20 recycling centers where locals bring plastic waste, which is weighed and purchased by Eco Brixs, creating income opportunities for the collectors. The recycled plastic is transformed into a variety of innovative Eco-Products such as bricks, pavers, fence posts, and face shields, generating revenue that sustains the cycle of plastic collection and product creation.

Eco Brixs has recycled over 350 tonnes of plastic waste and creating 3,000 income opportunities for local people. The organisation developed a unique plastic-sand composite paver that is stronger and more durable than concrete, supporting the construction and healthcare sectors. Partnerships with local entities such as the Masaka Diocese and Buganda Kingdom, as well as international organisations like Tearfund and the Queen's Commonwealth Trust, have further bolstered their efforts. Eco Brixs also focuses on disability employment and youth education initiatives, aiming to make a lasting positive impact on Uganda's environment and its people as the program continues to expand.

South Africa – Mechanical recycling: Outdoor furniture (Tufflex)

Tufflex Plastic Products (Pty) Ltd, founded in 1994, has established itself as a leading and reputable plastic recycling facility in Gauteng, South Africa. With nearly three decades of experience, the company specializes in recycling both post-consumer and post-industrial polyolefin waste, operating one of the most advanced plastic wash-plants on the African continent. Tufflex's commitment to innovation is evident in the development of a unique drying and processing line specifically designed to convert hard-to-recycle waste polyolefin powders back into usable pellets. This technological advancement underscores the company's dedication to addressing some of the most challenging aspects of plastic recycling, particularly in dealing with materials that are often deemed non-recyclable.

The company's operations extend beyond traditional recycling processes. Tufflex is distinguished by its production of a wide array of recycled plastic timber products, which are utilized in various industrial, agricultural, and domestic applications. These products include outdoor furniture, pallets, decking, dustbins, picket and other types of fencing, walkways, scaffolding sole boards, railway sleepers, and sundry DIY, industrial, and agricultural applications. The versatility of these products demonstrates the company's ability to repurpose waste polymers into high-quality, durable materials that serve a multitude of functions. Figure 61 show typical products, which are made by Tufflex from recycled plastic waste.

Figure 61. Outdoor furniture made by Tufflex from recycled plastic [99]

What sets Tufflex apart is its capability to recycle materials that are typically challenging to process. The company uses a variety of waste polymers, including those considered impossible to recycle, such as toothpaste tubes, mixed plastics, and multilayer substrates. By incorporating these difficult-to-recycle materials into its product line, Tufflex is not only diverting significant volumes of waste from landfills but also contributing to the creation of a circular economy in the region. This approach is a testament to the company's innovative spirit and commitment to environmental sustainability.

Furthermore, Tufflex operates with a strong focus on minimizing its environmental footprint. The company has implemented a zero waste to landfill initiative, where all polyolefin waste and scrap generated through conventional recycling processes are not discarded but are instead reintegrated into the production of recycled plastic timber. This closed-loop system not only reduces the need for virgin materials but also significantly lowers the environmental impact of the company's operations, making Tufflex a model of sustainability in the plastic recycling industry.

Tufflex's commitment to innovation and sustainability is driven by a highly experienced management team. The company was privately owned and led by Charles Muller who retired recently and sold the business, with key figures like Deon Swart overseeing technical operations, Michael Carlsson managing commercial activities, and Peter Sifo heading production. Collectively, the management team brings over 100 years of expertise in plastics and packaging, ensuring that Tufflex remains at the forefront of industry developments. Their combined knowledge and experience play a crucial role in the company's ongoing efforts to innovate, particularly in tackling difficult-to-recycle materials and expanding the company's capabilities in the recycling sector.

The company's motto, "Innovative Plastic Recycling," encapsulates its approach to business. Tufflex consistently seeks out new ways to address the challenges of plastic waste management, ensuring that its processes and products are both environmentally sustainable and economically viable. The company's ability to turn waste into valuable resources has positioned it as a leader in the industry, not only within South Africa but across the continent. As the global demand for sustainable waste management solutions continues to grow, Tufflex is well-positioned to expand its impact, contributing to a cleaner, more sustainable future through its pioneering recycling technologies [100].

Colombia – Mechanical recycling: Botellas de Amor (Bottles of Love)

Flexible plastic is one of the least recycled waste materials globally, leading to an increasing amount of discarded waste daily [101].

According to its brochure, the Love Bottles Foundation, a Colombian non-profit organization, addresses this issue by implementing a circular economy strategy to collect flexible plastic from the source and transform it into recycled plastic lumber (RPL). This RPL is used to build houses, playgrounds, and furniture for the market, as well as to donate to vulnerable populations, creating both environmental and social benefits.

Figure 62. Manufacture process RPL [101]

Their strategy involves raising environmental and social awareness, collecting flexible plastic waste, sorting it, and transforming it into RPL. The commercial sale of these products generates surplus funds, which are used to donate houses and playgrounds to vulnerable communities. Additionally, they collect post-industrial waste and encourage companies to join their impactful environmental and social project.

The bottles are collected and transported in the Foundation's vehicles to the selection plant. There, the bottles are opened, and the contents are selected. The selected plastic is agglutinated, where plastics gain weight through friction in a high-speed container. This bound material is filtered to remove metallic particles and then fed into an extruder machine. During extrusion, the agglutinated material is softened and transported by a screw to an-outlet nozzle, where it fills moulds of different shapes with the hot material. Afterward, the material undergoes a cooling stage for demoulding the Recycled Plastic Lumber (RPL). The RPL is then stored for later use in constructing houses and furniture, which are sold. The proceeds from these sales generate surplus funds used to donate houses, school classrooms, desks, dining tables, and playgrounds to vulnerable communities.

Figure 63. House built in Antioquia, Colombia [101]

New Zealand - Mechanical recycling: Lightweight aggregate (Plazrock)

Plazrok International Ltd (Plazrok) has pioneered an innovative approach to addressing the global plastic waste challenge by developing Plazrok, a lightweight composite aggregate specifically designed for a wide range of concrete applications. This technology leverages waste plastics and other materials, transforming them into a valuable resource that not only enhances the properties of concrete but also contributes to environmental sustainability by reducing plastic pollution.

Plazrok is the outcome of years of dedicated research and development, resulting in a product that according to Plazrok provides several technical advantages over traditional aggregates used in concrete production. One of the key features of Plazrok is its good compressive strength, which exceeds the performance of many conventional aggregates. This makes it a suitable replacement for traditional materials in various concrete applications, including those requiring high structural integrity. In addition to its strength, Plazrok offers also benefits in terms of weight reduction. Concrete produced with Plazrok can be up to 40% lighter than standard concrete, which has far-reaching implications for the construction industry. The lighter weight of Plazrok-enhanced concrete reduces transportation costs, increases payload efficiency, and facilitates easier handling during construction, all of which contribute to overall project cost savings. Despite being lighter, Plazrok concrete maintains the necessary durability and resilience, making it an ideal choice for both residential and commercial construction projects. Figure 64 shows the Plazrok aggregate, ready for its use as concrete aggregate.

Figure 64. Plazrok concrete aggregate [102]

Another notable advantage according to the company is the non-porous nature of Plazrok aggregates. Unlike traditional aggregates, Plazrok does not absorb water, ensuring that the water-cement ratio in concrete mixes remains consistent, which is crucial for achieving the desired strength and quality in the final product. This characteristic also means that Plazrok is less likely to contribute to moisture-related issues within concrete structures, thereby enhancing their longevity. Plazrok's contribution to environmental sustainability extends beyond its role in concrete production. By repurposing waste plastics, Plazrok helps to reduce the environmental impact associated with plastic waste, which is a significant global issue. The production of Plazrok involves converting non-recyclable plastics into a valuable aggregate, thus diverting these materials from landfills and oceans.

Recognizing the need for scalable solutions to the plastic waste problem, Plazrok has developed modular, container-based plants that can be rapidly deployed to various locations, including remote areas and regions with limited infrastructure. These modular plants are housed in 40-foot containers and come fully equipped with all the necessary machinery for shredding, granulating, and processing waste plastics into Plazrok. The design of these plants allows for flexible operation, either in batch mode for specific project needs or in continuous mode for ongoing production. The modular nature of the Plazrok plants makes them ideal for a variety of settings, from small businesses and start-ups to larger operations in regions with high plastic waste generation. These plants are particularly suited for island communities and other locations where traditional large-scale recycling infrastructure may not be feasible. By providing a turnkey solution that is both efficient and easy to operate, Plazrok enables communities to take an active role in managing their plastic waste and turning it into a valuable resource. Figure 65 shows a small-scale production facility of Plazrok aggregates.

Figure 65. Small scale production facility of Plazrok aggregates [103]

Plazrok 's commitment to customer support extends beyond the initial installation of the modular plants. The company provides comprehensive training for operational and maintenance tasks, ensuring that clients can maximize the efficiency and productivity of their

Plazrok plants. Additionally, Plazrok offers ongoing technical support, including remote assistance and regular updates to the technology, ensuring that the plants continue to operate satisfactorily.

Austria (Plasticpreneur)

Plasticpreneur is a company that focuses on developing, designing, and manufacturing small-scale plastic recycling machines. Founded on the principle of turning plastic waste into valuable resources, Plasticpreneur provides a comprehensive suite of technology and services that make plastic recycling accessible to various user groups around the world. With its modular approach, the company empowers individuals and organizations to explore, create, and manufacture recycled plastic products, fostering a circular economy and promoting environmental awareness.

Feedstocks

The company's machines allow users to recycle a wide variety of plastics, including HDPE, PP, PS, LDPE, PLA, ABS, and TPU.

Technology overview

Plasticpreneur's recycling process is simple yet effective, enabling users to convert plastic waste into high-quality products through six key steps:

- Collection and Sorting: Plastic waste is collected and sorted by type to ensure the highest quality end products.
- Washing and Drying: The sorted plastic is thoroughly washed and dried, preparing it for further processing.
- Shredding: The cleaned plastic is shredded into small flakes of various sizes, which can be used as feedstock for the next stages.
- Injection and Extrusion Moulding: Using heat and pressure, the shredded plastic flakes are melted and either injected or extruded into moulds.
- Moulds: Plasticpreneur offers a variety of aluminium and steel moulds, designed to produce a wide range of products from recycled plastic.
- Final Products: The recycled plastic is transformed into durable, high-quality products that can be used for numerous applications, from household items to industrial components.

Innovative Machines

Plasticpreneur's machines are designed with versatility and user-friendliness in mind, making them suitable for a wide range of applications, from educational purposes to small-scale manufacturing.

<u>The machines include:</u>

- Granulator: Cuts plastic into small flakes, which are essential for injection and extrusion processes.
- Manual Shredder: A twin-shaft shredder that allows users to manually shred plastic waste into flakes.
- Injection Moulding Machine: Converts shredded plastic flakes into new products by injecting them into moulds.
- Extruder: Melts and extrudes plastic flakes into continuous streams, which can be moulded or wrapped around objects.

Each machine is built to be energy-efficient, easy to operate, and maintenance-friendly, with components sourced from local suppliers in Austria. **Error! Reference source not found.** shows an Injection Moulding Machine and Figure 67 shows an Extruder from Plasticpreneur.

Figure 66. Injection Moulding Machine from Plasticpreneur [104]

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Figure 67. Extruder from Plasticpreneur [104]

Plasticpreneur´s machines and services are employed in over 90 countries across six continents, from remote regions to urban settings. The company's products are used by a diverse range of clients, including universities, schools, NGOs, design studios, and more.

In addition to providing recycling technology, Plasticpreneur emphasizes the importance of social entrepreneurship. The company offers training programs and workshops that equip individuals with the skills needed to establish and manage their own recycling centers, turning plastic waste into new products and creating new business opportunities. These programs also foster creativity and innovation, enabling participants to design, prototype, and manufacture products that meet local needs. Plasticpreneur is also dedicated to environmental sustainability. By transforming plastic waste into new products, Plasticpreneur not only reduces the amount of waste that ends up in landfills or the natural environment but also contributes to the reduction of carbon emissions associated with virgin plastic production.

By making plastic recycling accessible, affordable, and effective, Plasticpreneur is empowering people around the world to take control of their plastic waste, turning it into valuable resources and creating a more sustainable future. Figure 68 shows two typical products, which are produced by Plasticpreneur´s machines. New moulds for new application can be provided easily and is offering countless new applications.

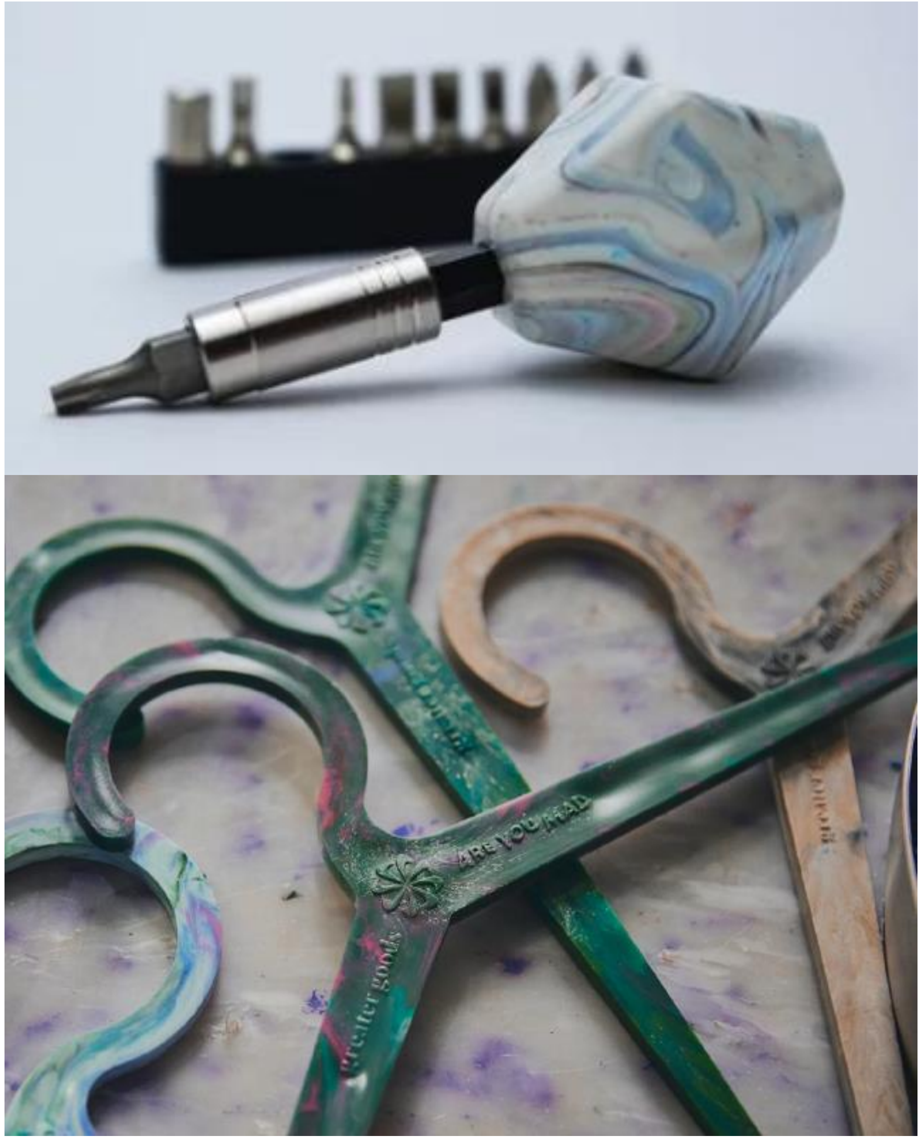

Figure 68. Typical products made with Plasticpreneur´s plastic recycling machines [104]

India - Plastic to Oil, Depolymerization, Fluxolysis

The technology evolves around the PyroMark R P2F (Plastic to Fuel) Plant, which is designed to convert waste plastics into useful fuels through a process called thermal depolymerization. Below is a detailed breakdown of the technology, including some specific numbers:

Technology Overview: *Thermal Depolymerization:* The process involves breaking down mixed plastic waste into simpler hydrocarbons at high temperatures. The technology employed is non-catalytic, relying on *magnetic flux-based heating to depolymerize* the plastics without causing air, soil, or water pollution.

Feedstock: The plant processes mixed plastics from municipal solid waste, including LDPE (Low-Density Polyethylene), HDPE (High-Density Polyethylene), PP (Polypropylene), PS (Polystyrene), and multi-layer/multi-colour packaging films.

Preparation steps: Plastics are first separated from other waste using Trommel and Air Classifier systems. The plastics are then subjected to an air cleaning process to remove impurities. The cleaned plastics are densified and reduced in size to 5-20 mm before being fed into the reactor.

Processing Capacity: The plant has a processing capacity of 3 tonnes per day (TPD) of plastic waste but can be scaled up as it is a modular technology.

Outputs: For every tonne of plastic waste processed, the plant produces:

500-600 kg of Liquid Oil (Light Diesel Oil - LDO), accounting for 50-60% of the input. 250-300 kg of Carbon Char, which is 25-30% of the input. 10-25% of the input is converted into Mixed Hydrocarbon Gas, which has a calorific value similar to LPG.

Process Efficiency: The plant achieves a high oil yield of over 50-60% of the input plastic waste. The treatment process involves a high-temperature environment where the feed material is cracked and vaporized using magnetic fluxolysis.

Plant Operations:

- Land Area: The plant occupies an area of 10 meters x 10 meters x 7.5 meters (LxBxH). Manpower: The plant requires 4 personnel to operate, including 1 engineer, 1 supervisor, 1 labourer, and 1 operator.
- Operational Expenses:
- Monthly operational costs include salaries, electricity charges, and consumables, totaling Rs. 168,500 (USD 2000) per month.

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Revenue Generation:

The plant generates revenue by selling the produced oil and carbon char:

Oil Sales: 5.5 tonnes of oil sold at Rs. 32 per liter generate Rs. 176,000. Carbon Char Sales: 2.7 tonnes of biochar sold at Rs. 12 per kg generate Rs. 32,400. Total revenue per month amounts to Rs. 208,400.

Environmental and Regulatory Compliance:

- Pollution Control: The plant operates without causing wastewater discharge, stack emissions, odours, or open flames, aligning with environmental standards.
- Regulatory Approvals: The plant has applied for necessary clearances from the Pollution Control Board and petroleum safety approvals (PESO).

The PyroMark R P2F Plant in Vyara Nagarpalika in Gujarat, India represents a unique waste management solution, particularly in converting plastic waste into valuable fuel products. The plant's ability to process mixed plastics efficiently, coupled with its financial viability, could make it a promising model for replication in other regions seeking sustainable waste management solutions.

Indonesia – Pyroysis: Geo Trash Management

Geo Trash Management (GTM) is a company focused on developing waste-to-resource systems that assist regional governments in establishing effective waste collection and processing strategies. Their decentralized recycling facilities convert plastic and organic waste into valuable commodities, which are then sold to generate revenue and support local economies. The company employs pyrolysis technology to convert non-recyclable plastics into fuel and other marketable products.

GTM's facilities are designed to be located near landfill sites to capture methane gas as a fuel source or to include organic bio-digesters to generate methane from organic waste. Their recycling systems aim to transform zero-value plastics into useful resources, such as pyrolysis oil, which can be processed further into various fractions for use in producing new plastics or as substitutes for fossil fuels. Additionally, GTM focuses on motivating communities to participate in waste collection by creating buyback systems that change the perception of plastic's value.

Pyrolysis Technology and Resource Transformation: GTM's waste-to-resource systems utilize pyrolysis technology, which is a thermal conversion process conducted in a zero-oxygen environment. During this process, the hydrocarbons in plastics are broken down into shorter chains, which are then cooled into a liquid known as pyrolysis oil. The oil undergoes further refinement through fractional distillation to separate it into different fractions. Some of these fractions can be used to create new virgin-grade plastics, while others serve as substitutes for fossil fuels like gasoline, jet fuel, and diesel. The process also produces hydrogen gas, which is recirculated back into the heating systems, making the operation highly efficient. Figure 69 shows a pyrolysis plant of GTM in Indonesia.

Figure 69. GTM pyrolysis plant in Indonesia [105]

Supporting Regional Economies: GTM's operations are spread across Indonesia and Australia, with plans to expand their impact by building multiple plants in different regions. Each facility has the capacity to handle 30 tonnes of waste plastic and 100 tonnes of organic waste per day, suitable for communities with populations of over 200,000 people. The company's approach supports local economies by involving local contractors and employees in the construction, operation, and maintenance of these waste management facilities. After a 20-year operational term, the facilities are handed over to regional governments, ensuring long-term sustainability and local ownership.

Environmental and Economic Impact: GTM's focus is not just on recycling but also on transforming plastic waste into valuable resources that contribute to the circular economy. Through their buyback systems, they encourage community participation in plastic waste collection, offering financial incentives to individuals and community managers. This inclusive model helps change the perception of plastic waste, making it a valuable commodity rather than a pollutant. GTM's goal is to increase Indonesia's plastic recycling rate, which currently stands at around 10%, to as much as 89%. The company's operations, driven by their mission to make plastic valuable, will help recycle millions of tons of waste over the next two decades, with the potential to expand into other regions.

Comprehensive Waste Management Solutions: In addition to plastic recycling, GTM's systems are designed to handle organic waste as well. Where landfill gas extraction is not feasible, the company uses organic bio-digesters to generate methane gas. This methane can be used to fuel the pyrolysis process, further reducing reliance on external energy sources. The company's closed-loop system ensures that gases generated during pyrolysis are reused to power the facilities, minimizing environmental impact and supporting a more sustainable waste management system.

Future Expansion and Impact: Looking ahead, GTM plans to scale up its operations across Lombok, East Kalimantan, Sumbawa, and Bali. The company envisions a network of 10 recycling plants that will not only generate revenue but also create jobs, reduce landfill use, and significantly increase recycling rates. Over a 20-year lifespan, GTM's facilities are expected to recycle up to six million tons of plastic and organic waste, turning waste into a valuable resource for communities.

Australia – Collaboration between Curbylt and iQRenew for soft plastic recycling

The partnership between CurbyIt and iQRenew represents a significant step forward in Australia's efforts to tackle the challenge of soft plastic waste. Through this collaboration, both companies have effectively combined their strengths to create an innovative and scalable solution for collecting, processing, and recycling soft plastics, a material traditionally considered difficult to recycle.

CurbyIt: Engaging Communities for Soft Plastic Collection

CurbyIt's approach to soft plastic recycling is community-focused and user-friendly. Partnering with local councils, CurbyIt enables households to recycle their soft plastics directly through their existing yellow recycling bins. The process is simple: participants download the Curby app, fill their CurbyBags with clean soft plastics, attach a CurbyTag, and scan it with the app before placing the bag in their recycling bin. This method not only simplifies the recycling process but also engages the community through a fun and interactive app that tracks the recycling journey of each bag, ensuring transparency and encouraging continued participation. Figure 70 shows the plastic bags and mobile phone app of the Curbylt soft plastic recycling system.

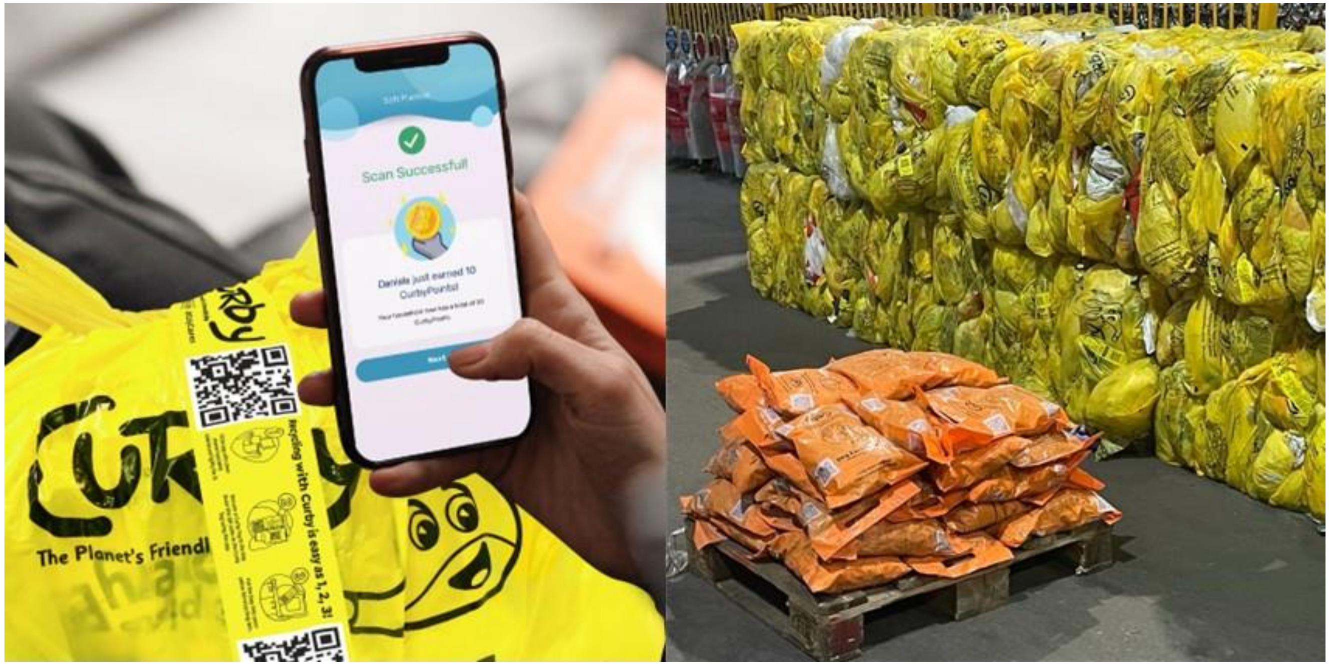

Figure 70. Plastic bags and mobile phone app of the Curbylt soft plastic recycling system

iQRenew: Advanced Recycling Infrastructure

iQRenew complements CurbyIt's collection system by providing the necessary infrastructure to process the collected soft plastics. Located in Taree, New South Wales, iQRenew's Soft Plastics Engineered Commodity (SPEC) facility is Australia's first site dedicated to processing post-consumer soft plastics. The facility uses advanced mechanical recycling processes to sort the plastics into various grades of feedstock, which are then used in different manufacturing applications. Figure 71 shows the soft plastic sorting facility of iQRenew.

Figure 71. Soft plastic sorting facility of iQRenew [107]

The Recycling Process

Once collected by CurbyIt, the soft plastic waste is transported to iQRenew's SPEC facility, where it undergoes a series of sorting and processing stages. The SPEC facility is designed to handle 100% post-consumer soft plastics, transforming them into high-grade feedstock suitable for both chemical and mechanical recycling processes.

The output materials are categorized into three grades:

- A-Grade Product: This high-quality feedstock is suitable for chemical recycling processes and can be used to produce new plastic products, thereby closing the loop in the plastic value chain.
- B-Grade Material: Ideal for making recycled pellets, which are then used in the production of non-food grade films, construction materials, agricultural products, and various other plastic items.
- C-Grade Material: This grade is used for products made from extrusion moulding, such as park benches, bollards, fence posts, and other similar items.

Impact and Future Outlook

The alliance between CurbyIt and iQRenew is a significant development in Australia's recycling landscape. By providing a seamless end-to-end solution for soft plastic waste, this partnership not only helps reduce the volume of plastics sent to landfill but also contributes to the circular economy by turning waste into valuable resources. With ongoing expansion plans and the potential to roll out the CurbyIt system across more councils and regions, this partnership is poised to make a substantial impact on Australia's ability to manage and recycle soft plastics effectively.

This case study underscores the importance of collaboration between technology providers, local governments, and the community in addressing complex environmental challenges. Through their combined efforts, CurbyIt and iQRenew are not only transforming how soft plastics are managed but are also paving the way for a more sustainable and circular future.

Technology comparison

In order to allow for a systematic review of plastic recycling technologies with regard to their performance to recycle low value plastic a set of criteria has been developed and applied to assess a selection of technologies. Section on the **Methodology for comparing plastic recycling solutions** explains the reasoning of the criteria selection as well as the methodological approach of the technology comparison and in the following section **(**

Short description of assessed plastic recycling and plastic recovery solutions**)** the technologies that are compared are briefly described.

Methodology for comparing plastic recycling solutions

The suitability of a specific plastic recycling technology is highly context-dependent, influenced by various factors such as the status of the local waste management system, the type of plastic waste, the demand for recycled plastic products or polymers, the existence of processing industries capable of utilizing recycled plastic feedstocks, and the urban versus rural setting, among others. This chapter presents an assessment matrix designed to facilitate the comparison of different plastic recycling technologies and recovery solutions. A set of parameters was carefully selected, in collaboration with CATALYTIC Finance, to ensure comprehensive coverage of all relevant dimensions for this assessment. These parameters were chosen based on expert market knowledge and research conducted as part of this study. The objective was to include a diverse range of potential solutions, representing the full spectrum of plastic recycling and recovery technologies. It is important to note that while this study aims to cover a wide array of solutions, there may be other innovative approaches currently in development. However, due to their early stages or limited significance, they have not been included in this comparative analysis.

The technologies have been grouped in four categories: Mechanical recycling, Chemical Recycling, Biological Recycling and Other Recovery solutions. It must also be stressed once again that anyone of these technologies require prior collection as well as prior sorting of the waste input stream in order to ensure that requirements based on the recycling process or as well the product to by produced from the recycled plastics are met.

The proposed methodology allows to get an overview about the characteristics of each recycling technology and its strengths and weaknesses. No recommendations are done for or against a specific technology because, as already mentioned, such a decision is very context dependent. A solution which might be very suitable for a developed country, or an emerging country with functioning waste management system, might be not the right choice for a country without such a waste management system. Often a bridging solution might be the right choice at the beginning in order to improve the current situation and to start with the valorization of plastic waste. In the long term other more suitable solutions might evolve out of these bridging solutions.

The parameters, which have been defined for the plastic recycling comparison, have been grouped in the following categories:

- Requirements for the input of the recovery process
- Process aspects / requirements
- Output of the recovery process
- Sustainability aspects
- Investment aspects

For each of these categories several parameters have been defined and a corresponding evaluation key. In the following tables each of the selected parameters is described, the reason why it has been selected and the evaluation key is provided.

Requirements for the input of the recovery process

In Table 1 the criteria for the assessment are described briefly, the reasoning for selection as well as the evaluation key is explained.

Table 1. Criteria set with regard to input requirements

Parameter	Description	Relevance	Evaluation key
Need for plastic feedstock security	How critical is for the recycling technology a stable and continuous supply with waste feedstock?	For some technology a continuous operation is key in order to allow economic viability. For others a batch operation with interruptions is possible without any negative consequences. Especially for solutions with a high CAPEX feedstock security is essential.	High-low
Non-plastic impurities	How critical is it that the input feedstock is free of non-plastic impurities?	Certain technologies allow the processing of mixed and contaminated waste without influencing significantly the output quality of the recycling product. Other technologies require very homogenous and clean plastic waste without impurities in order to work properly. This also very much depends on the actual implementation approach of a certain technological solution in a given context. Either one relies on the provision of feedstock of a certain quality or the pre-conditioning needs to be implemented on top of the recycling solution itself.	Highly sensitive-robust
Defined polymers/mixed plastics	Is the technology suitable for mixed plastic wastes, or is it only suitable for a specific defined polymer?	Certain technologies due to the product aimed for can be used just for a specific polymer type and are not suitable for mixed plastic waste or multifilm plastic waste. Others are flexible in processing of mixed polymer wastes and can handle a mix of polymer types.	Highly sensitive-robust
Preconditioning requirements	What type of pre-conditioning is required in order to process the plastic waste with a certain technology?	Specific technologies can have very different pre-conditioning requirements for the plastic waste before the waste can be processed. Typical pre-condition requirements are sorting, cleaning, shredding (size level), control of the moisture content, etc.	Low-excessive

Process aspects / requirements

In Table 2 the criteria for the assessment are described briefly, the reasoning for selection as well as the evaluation key is explained.

Table 2. Criteria set with regard to process requirements

Parameter	Description	Relevance	Evaluation key
Technology readiness level	How mature is the technology with regard to its commercial use on a larger scale?	There are many plastic recycling technologies under development, but many of them are in early stages of development and not for all of them it is guaranteed that they will reach a technological maturity high enough to be applied on a larger scale and to be attractive for investors.	The typical Technology Readiness Level (TRL) scale for new technology is used, but has been adapted. Additional to 9 categories: [Basic research (1), Applied research (2), Critical Function or Proof of Concept (3), Lab Testing/Validation of Alpha Prototype (4), Laboratory Testing of Integrated/Semi-Integrated System (5), Prototype System Verified (6), Integrated Pilot System Demonstrated (7), System Incorporated in Commercial Design (8), System Proven and Ready for Full Commercial Deployment (9)] three additional categories have been created [successfully operated pilot plants (10), successfully operated first phase of a commercial plant with expected commercial success (11), fully commercial plant operation with track record of commercial success (12)
Throughput per unit / plant	What is the capacity of processed plastic waste, which can be recycled in a continuous form per time period?	Recycling technologies for different capacities are on the market. Some of them are from a technology or economical point of view just viable above a certain processing capacity, others are also suitable for small plastic waste streams.	Defined throughput thresholds (order of magnitude): >10 kg/h >100 kg/h >1 t/h >10 t/h

Parameter	Description	Relevance	Evaluation key
Level of automation	How much automation does the technology set-up rely on?	Automation is a key factor for the scaling up of technologies. On the other hand for specific contexts in the Global South less automation might be an advantage due to a lack of skilled workforce, job creation and the relatively low salaries.	Very low low medium high very high
Complexity level	How sophisticated in technical terms is the recycling technology?	The broad spectrum of already implemented or currently under development recycling technologies have very different complexity regarding the technological set-up. Especially for advanced recycling technologies the complexity level for some of them is rather high. In the context of the suitability of recycling technologies the technology complexity is of high relevance because not for all locations a too complex technology will be suitable due to lack of trained experts, maintenance issues, etc. Although complex solutions require high CAPEX and OPEX.	Very low low medium high very high
Decontamination yes/no	Does the technology allow to divert contaminants in the plastic waste from the final recycled output product? (e.g. removal of additives or heavy metals, etc.)	The contamination of plastic waste can be seen as one of the biggest challenges for the recycling of plastic waste. The aim of plastic recycling should not be to cycle contaminants around and lose traction of it. In a functioning circular economy system such contaminants should be extracted from the material use circle in order to guarantee that reused feedstock is as clean as possible, what guarantees its versatile reuse. Especially in cases where on the collection and sorting level little selection / source separation of the material feed is done a decontamination becomes very important.	Yes / No
Additional feedstock	Some recycling processes require additional feedstock to the plastic waste. For example mineral components if the recycled product is to be used in construction	Mixing plastic waste with other types of material may lead to the loss of the plastic from the plastic recycling cycle as well as might impede to recycle the other material mixed with the plastic as well.	Yes / No, which one?

Parameter	Description	Relevance	Evaluation key
	substituting ordinary concrete or asphalt.		

Output of the recovery process

In Table 3 the criteria for the assessment are described briefly, the reasoning for selection as well as the evaluation key is explained.

Table 3. Criteria set with regard to output of the recovery process

Parameter	Description	Relevance	Evaluation key
Main product of the process	What is the output product and how can it be used?	Different recycling technologies produce different output products. E.g. Polymers, Monomers, Carbohydrates, etc. or already usable products made out of plastic. This is relevant regarding the insertion of a recycling technology into the local context. E.g. if there is an offtake market for the output products, or does the technology produce an output feedstock, which has to be further processed in order to be of any use.	plastic feedstock food-grade plastic feedstock non-food-grade feedstock for petrochemical industry plastic product other non-plastic product with plastic addition
Usable by-product	Does the process produce any other by-product, which might be interesting for sale?	Some recycling processes generate on top of the recycled plastic also other products, which could be of commercial interest in order to guarantee a commercial viability of the technology.	e.g. heat, electricity none
Rejects	Are there any rejects as consequence of the recycling process?	Rejects are material streams which cannot be further used and which are accumulated as consequence of the recycling process. Such rejects eventually can be hazardous waste (e.g. extracted contaminants) or materials without further use, which have to be disposed in a save manner.	Categories: Percentage of rejects: 10% - 80%
Air emission	Are there any dangerous air emissions which are emitted due to the recycling process? [Has to be seen under the local Indonesian legal context regarding air emission limits]	Recycling technologies should be save for operators, neighbourhoods and the environment. Not all technologies can guarantee that during the recycling process all dangerous air emissions are contained. Emissions could harm e.g. workers which operate the recycling plant or neighborhoods, etc.	yes, scrubbing in place yes, no scrubbing no emissions
Product yield per tonne of plastic waste input	How much output is produced per tonne of input waste?	This factor is describing the efficiency of the recycling process.	<0,5 t 0,5 - 1,0 t <1,0 t

Sustainability aspects

In Table 4 the criteria for the assessment are described briefly, the reasoning for selection as well as the evaluation key is explained.

Table 4. Criteria set with regard to sustainability aspects

Parameter	Description	Relevance	Evaluation key
Circular economy principles	Is the technology supporting a circular economy, what results in the recovery of high value feedstock for further processing or is the technology deteriorating the quality of the output material stream.	For a truly circular economy it is important that the output material of the recycling process is aiming to maintain the quality of the used virgin feedstock. Not all recycling technologies allow this claim and result in a loss of quality of the received output product (downcycling). Sometimes recycling technologies are proposed that do not aim to recycle the material itself but rather to use it as a replacement for a different material.	closed loop recycling down-cycling other recovery
Social inclusion / job generation	Does the recycling technology support the social inclusion of vulnerable groups and achieve local job creation? (Indonesian context)	The socio-economic context for a specific location where a recycling plant will be located is of high relevance in order to be successful. This parameter has been evaluated under consideration of the local social context in Indonesia.	enabling entrepreneurship feasible for existing businesses only
Revenue generation potential	Does the recycling technology allow the generation of revenues and how high is this revenue generation potential? (Indonesian context)	The success of a recycling technology depends on many local factors. The potential to generate revenue streams for the local communities and local business is one of the key factors, which has to be considered. E.g. if there is no local off-take market for the produced output products a technology, which might be very suitable from a technological point of view, will not prevail under the local context. This parameter has been assessed based on	High Medium Low None

Parameter	Description	Relevance	Evaluation key
		the local context in regards of the revenue generation potential.	
Greenhouse gas emission savings / energy aspects	How far is the assessed plastic recycling technology contributing to climate mitigation efforts? How energy efficient is the process? (Indonesian context) [This is highly local context specific and for quantitative figures a detailed Life Cycle Assessment (LCA) for each recycling technology would be required. Therefore, just a qualitative assessment has been undertaken]	There is a significant difference in regards of conversion efficiency of plastic recycling technologies, what has direct implications regarding its potential to contribute to mitigate the emissions of GHGs. On one hand it is relevant how much virgin fossil-based feedstock for the production of plastic can be replaced by recycling, on the other hand the overall energy requirement related to pre-conditioning of waste and during the complete recycling process have to be considered. Or if the output product is used as fuel or in a material way.	High positive impact High negative impact
Size of product market	What is the market potential for the commercialization of the recycled output product? (qualitative assessment)	For the scaling-up and roll-out of a plastic recycling technology it is of high relevance what is the size of the market for the output product. Plastic recycling technologies differ regarding the quality and type of output products. This parameter is assessing on a qualitative basis the market potential for the sale of the output product(s).	Low Medium High
Environmental aspects	Is the recycling technology contributing to lead to an overall improvement of environmental factors? (e.g. Improvement on air quality, reducing soil contamination, avoiding	As humanity is facing multiple environmental challenges it is important to follow a holistic view regarding the environmental assessment of a recycling technology. It is important to avoid that a technology might contribute to solve one environmental challenge (e.g. marine plastic litter), but at the same time is aggravating other	Low Medium High

Parameter	Description	Relevance	Evaluation key
	water contamination, avoiding microplastic contamination)	environmental problems (e.g. microplastic dissemination)	
Resource efficiency compared with Indonesian baseline	The aim is here to compare the resource efficiency of the recycling technology with the baseline scenario in Indonesia.	Recycling aims at substitution of virgin material. The more virgin material can be substituted the higher the resource efficiency.	Low medium high

Investment aspects

In Table 5 the criteria for the assessment are described briefly, the reasoning for selection as well as the evaluation key is explained.

Table 5. Criteria set with regard to investment aspects

Parameter	Description	Relevance	Evaluation key
Centralized / decentralized	Is the assessed plastic recycling technology following a centralized or a decentralized implementation concept?	Some plastic recycling technologies are suitable to be implemented in a small, decentralized way, others require large-scale industrial set-ups in order to be technological and/or economically feasible. Large centralized industrial plants in general have the advantage to be more cost efficient per tonne of processed plastic waste, but might have the disadvantage that they are capital intensive, require large quantities of stable feedstock supply and often depend on the existence of a local industrial ecosystem, where the can be inserted. (e.g. further processing of recycled output products, or as final off-taker of the output product)	Small scale industrial scale

Parameter	Description	Relevance	Evaluation key
Minimum investment volume per plant (critical size)	What is the typical investment required for the installation of one single recycling plant? Is there a critical size for a successful operation?)	This parameter is aiming to give a rough understanding about the required investment volume for the assessed recycling technology. Because this for some technology providers is highly sensitive information, this assessment has been undertaken also based on publicly available information and based on the knowledge of waste experts. Just an order of magnitude can be provided for most of the assessed technologies as exact numbers are very context specific and are not being disclosed by technology providers.	10,000 US-$ 100,000 US-$ 1,000,000 US-$ >50,000,000 US-$ n.i.a. = no information available
CAPEX per tonne treatment capacity	What is the CAPEX needed for the installation of the recycling technology per tonne of waste processing capacity? (related to waste input) [Because of lack of data this assessment is based on a qualitative evaluation in comparison to other technologies]	This parameter describes the CAPEX needed for the installation of the assessed technology per tonne of processing capacity of input plastic waste.	High medium low
CAPEX per tonne of product output	What is the CAPEX needed for the installation of the recycling technology per tonne of recycled output product?	What is the CAPEX required for the installation of one tonne output product capacity? This is different to the CAPEX required for one tonne of input waste capacity due to different process efficiencies.	High medium low

Parameter	Description	Relevance	Evaluation key
OPEX per tonne treatment	What OPEX costs have to be considered for the operation of the plant?	There are large differences regarding OPEX requirements to operate different plastic recycling technologies. E.g. regarding energy needs, labour costs, water consumption, tipping fees for rejects, catalysts, solvents, etc.)	High medium low

Short description of assessed plastic recycling and plastic recovery solutions

In the following sections all technologies that have been assessed according to the methodology presented in the section on **Methodology for comparing plastic recycling solutions** are presented with a short profile.

In total, thirty-seven (37) technologies were identified in this study. when selecting case studies for a detailed evaluation of LVP recycling technologies, the focus was on criteria that reflect both the specific needs of Indonesia and the practicalities of implementing these technologies.

<u>The selection was made based on the following aspects:</u>

Relevance to Low and Middle-Income Countries: The selected case studies have been chosen primarily because they demonstrate technologies that are particularly suited to the socio-economic and infrastructural realities of low and middle-income countries. These regions often face unique challenges, such as limited waste management infrastructure, financial constraints, and a higher prevalence of low-value plastics in the waste stream. By focusing on technologies that have shown promise or success in similar contexts, these case studies provide practical insights into scalable solutions that can be adapted to other regions with similar profiles.

Availability of Detailed Information: A key consideration in selecting these case studies was the depth and quality of the information available. The availability of information has depended on the online literature and the willingness of technological providers to share their information. The ability to obtain detailed technical, operational, and financial data from the technology providers has allowed for a more thorough evaluation. This ensures that the findings are robust and applicable to decision-makers in the field.

Commercial Success and Market Viability: Another factor in the selection process was the proven commercial success of these technologies. In low and middle-income countries, where financial resources are often limited, it is crucial to consider technologies that are technically feasible and commercially viable. The selected case studies highlight technologies that have demonstrated a clear path to market success through cost-effectiveness, scalability, or the ability to generate revenue streams, such as through the sale of recycled products or energy recovery.

Selected “other recovery” technologies

African Solutions [108]

African Solution, established in 2001 and relaunched in September 2018, is a Social Business Enterprise (SBE) based in Mogadishu, Somalia. Dedicated to transforming waste into valuable resources, the organization integrates both “For Profit” and “Not-for-Profit” initiatives to address environmental challenges, promote climate action, and contribute to sustainable development and poverty reduction.

Founded by Abdi Hirsi Ali, a professional architect-urban planner, lawyer, and eco-activist, African Solution plays a pivotal role in environmental protection and socio-economic development. The company’s activities include clean-up and sorting of various plastics, such as PET, PVC, HDPE, LDPE, PS, and PP, which are then used as input materials for their production processes.

African Solution specializes in the production of eco-friendly building materials, including roof tiles, paving stones, wall bricks, fencing posts, and outdoor furniture. These products are manufactured through a proprietary extrusion process that operates at temperatures exceeding

220°C, using carefully selected plastic waste combined with sand and UV-stabilizing additives. This process ensures the durability and UV resistance of the products, making them suitable for the harsh climate of Somalia.

The company's down-cycling approach, which converts plastic waste into durable building materials, not only helps reduce environmental pollution but also supports the local economy by creating jobs and providing affordable construction materials. African Solution's commitment to sustainability and innovation makes it to an interesting example for promoting a circular economy in Somalia, contributing to a better future for the region.

Bamboo House India [109]

Bamboo House India, based in Hyderabad, is a pioneering Social Business Enterprise (SBE) that merges sustainability with innovation to address pressing environmental concerns, particularly plastic waste. Founded in 2006 by first-generation entrepreneurs Prashant Lingam and Aruna Kappagantula, the enterprise was born out of a need for eco-friendly furniture and has since evolved into a multifaceted organization that supports rural and tribal artisans by utilizing bamboo and recycled plastic waste as versatile, eco-friendly building resources.

India is the world's second-largest producer of bamboo, yet many rural artisans, despite their exceptional craftsmanship, earn meager incomes due to limited market access. Bamboo House India seeks to bridge this gap by providing livelihood opportunities to these artisans while promoting bamboo as a sustainable building material in urban markets. The enterprise also extends its environmental efforts by recycling plastic waste, tyre waste, banana fiber, agricultural waste, textile waste, cane, water hyacinth, and other materials, thereby contributing to the green and circular economy.

Bamboo House India's approach includes also the production of a wide range of utility products from recycled plastic, including mobile phone cases, USB sticks, flower-pots, furniture, and more. The enterprise's model is particularly suited for urban local bodies (ULBs), women-led enterprises, self-help groups (SHGs), startups, educational institutions, NGOs, and small-scale units, offering a sustainable solution with a low investment need.

In addition to these innovations, Bamboo House India also produces plastic sheets for houses and shelters, applying down-cycling techniques to transform plastic waste into products.

Tufflex Plastic Products [110]

Tufflex Plastic Products Ltd. is a South African company specializing in the recycling and reprocessing of polyolefin plastic waste. Established in 1994, the company operates a recycling facility in Gauteng, where it processes both post-consumer and post-industrial plastic materials.

Tufflex's core operations involve recovering value from plastic waste streams that would otherwise be destined for landfills. The company's recycling processes include a plastic washing plant capable of handling a wide range of contaminated materials. Tufflex has developed expertise in transforming difficult-to-recycle plastic waste, such as multi-layer substrates and toothpaste tubes, into usable products.

Besides closed loop mechanical recycling of polyolefin waste rejects from that process (mixed plastics) are used for recycled plastic timber products, which are employed in various sectors including construction, agriculture, and domestic applications.

This second part of the recovery operation is classified to be other recovery and down-cycling compared to the polyolefin closed loop recycling.

Ecopals [111]

Ecopals produces EcoFlakes, a polymer modification for asphalt using recycled plastics. EcoFlakes are designed to replace newly produced plastics in asphalt with recycled materials that would otherwise be incinerated. The product is used to modify bitumen that is used for asphalt production either prior to or directly at the asphalt mixing plant.

The feedstock for Ecopals is already heavily sorted and preconditioned mixed post-consumer plastic waste that cannot be mechanically recycled yet which is sorted according to specifications and received by Ecopalse as a product and not as a waste.

The EcoFlakes are composed of a blend of different polymers and compatibilizers that enhance the bonding with bitumen. The production process involves testing for contaminants and emission stability to ensure quality control. EcoFlakes can be used in temperature-reduced and recycled asphalt and are designed to be compatible with various road construction applications.

Even though the recycled plastic used according to the Ecopals approach is lost from the plastics material loop this technology can be seen as resource efficient wherever virgin plastic used for asphalt production is replaced.

Plazrok / Enviroplaz [112]

ENVIROPLAZ is a company based in New Zealand, which developed a patented product, called PLAZROK, as lightweight aggregate for the construction industry. Plazrok is based on a technology that transforms waste plastic into a lightweight aggregate material suitable for use in concrete production. The company positions its product as a solution to two pressing environmental challenges: plastic waste and the demand for sustainable building materials.

Plazrok-incorporated concrete offers several potential advantages over traditional concrete, including reduced weight, improved thermal and acoustic properties, and increased strength. These characteristics make it suitable for a range of applications, such as concrete panels, floor toppings, and ready-mix concrete. Additionally, the use of recycled plastic in Plazrok aligns with sustainability certifications and initiatives, making it an attractive option for environmentally conscious construction projects.

While Plazrok demonstrates potential as a value-added product for the concrete industry, several factors will influence its market success. These include the cost-competitiveness of the material compared to traditional aggregates, the scalability of the production process, and the overall environmental impact of the technology, including energy consumption and waste management considerations.

The Plazrok process aims at replacing mineral products for certain lightweight applications by plastic based light weight aggregate. Recycling of the plastic after end-of-life of the light-weight products is possible in principle, however, requires specific collection and processing efforts that are yet to be developed as part of the construction sector.

Dauruland.id [113]

Daurulang.id offers a waste processing system for organic and low value plastic waste such as styrofoam, diapers, pads, multilayered plastics. Having 'zero waste to landfill' as their vision, the plastic waste that would often end up abandoned are processed into composite materials used for building blocks and organic waste into vermicompost. 40% of their daily capacity is aimed to process low value plastics. Prior to moulding into composite materials, low value plastic waste is shredded, dried, and melted. The product does not spread fire, is said to be durable and strong, and does not contain heavy metals. However, the system still relies on manual labour at its waste segregation point. Its simple configuration makes the system versatile and suitable for installation in a variety of settings, from living quarters and small-scale industries to large-scale operations. The upcycling of low-value plastics into composite materials, which possess qualities comparable to traditional building blocks, contributes to the sustainability of this business.

Rebricks.id [114]

Rebricks is a company that recycles plastic waste into building materials. Rebricks focuses on using rejected waste, such as soft plastic packaging, multilayer sachet packaging, plastic bags, beverage labels, and bubble wrap. The waste is processed into paving blocks, bricks, and rosters, raw materials for building materials. This business was formed in 2019, but research has been ongoing since 2018. This startup has succeeded in increasing the use of plastic waste 5 times from at least 1,000 kg in 2020 to 5,000 kg in 2021 and is expected to increase again in 2022. Until March 2022, it has used 3,500 kg of plastic waste, because every $1m^2$ of paving block contains at least 880 sachets of waste. Rebricks can reach 100 m^2/day per day, around 88,000 sachets of waste can be reduced per day. The company currently employs 10 workers.

Rebricks material is durable (can be used for more than 20 years) and can withstand loads of up to250 kg per cm^2. Rebricks collects almost 50 kg of plastic waste per day. The waste is then chopped twice, mixed with other formulas, treated/cured for 21 days, then molded into paving blocks and other products. This business was built to be a new solution while providing added value to rejected waste without adding new environmental problems such as not using any combustion process that produces smoke and not placing shredded plastic on the top surface of paving blocks.

Rebricks is a business that uses a bootstrapping system (relying on personal funds as capital). So, all decisions must be taken carefully and on target so that there are no major losses. Developing a business is still a challenge. One of the successes of this innovation is due to the support of good research and development. Research and upgrading knowledge periodically need to be done to understand market characteristics and adjust the products made. Conduct standardized tests because it requires a large amount of capital.

Selected “mechanical recycling” technologies

Plastikpreneur [115]

Plasticpreneur is a purpose-driven, impact-oriented social business focused on transforming plastic waste into new, usable products through small-scale mechanical recycling machines, which are sold to communities, entrepreneurs, NGO´s, etc. in order to allow their clients to valorise locally collected plastic waste and transform it in useful simple plastic products. By empowering communities to creatively repurpose sorted and clean plastic waste, the company contributes to the transition from a linear "take-make-dispose" economy to a circular one. With commercial activities in over 70 countries and more than 600 machines sold worldwide, Plasticpreneur continuously integrates customer insights into its product and service development, fostering environmental awareness at every step. Their machines enable the production of a variety of daily-use items, such as flowerpots and benches, clothing hooks, combs and many mores. The moulds to produce these products can be tailored to local needs.

Plasticpreneur therefore is to be seen as equipment provider rather than a recycler by itself.

Tufflex Plastic Products [110]

See description above, Tufflex is also providing plastic recyclates to be used for poly-olefine closed loop recycling.

Swedish Plastic Recycling [116]

Swedish Plastic Recycling is focused on ensuring that all plastic packaging in Sweden is recycled into new products. The company has built Europe's largest and most advanced plastic recycling plant, Site Zero, located in Motala. This facility is designed to process up to 200,000 tonnes of plastic packaging annually, sourced from households across Sweden. Site Zero uses fully automated technology with 60 NIR sensors, allowing for the sorting of twelve different types of plastics. The plant operates with a high level of efficiency, capable of sorting up to 95% of the received plastics, which are then prepared for further recycling processes. Any residual materials are directed to chemical recycling or converted into composite products.

Swedish Plastic Recycling aims to integrate the recycling process into the broader waste management system, working with producers to select recyclable plastic packaging and ensuring that waste collection systems are optimized. The company's ownership includes Plastinformationsrådet, Dagligvaruleverantörerna DLF, Svensk Handel, and Svensk Dagligvaruhandel, with around 100 employees. Their operations are supported by investments totaling approximately SEK 1 billion, including financing from the Swedish Environmental Protection Agency through the Klimatklivet climate investment aid program.

PreZero [117]

PreZero is a European company specializing in the recycling of post-consumer and industrial plastic waste. Since its founding in 2009, originally as GreenCycle, a department within the retail company Lidl focused on waste disposal logistics, PreZero has grown into the environmental division of the Schwarz Group. The company focuses on transforming waste into high-quality raw materials through advanced processes, contributing to a sustainable, circular economy. PreZero's recycling process includes the collection of plastic waste, followed by shredding, washing, sorting, drying, extrusion, and pelletization. This results in customized plastic recyclates tailored to meet the specific requirements of various industries, such as automotive, construction, household appliances, and gardening. The company's product lines, including Skyfil, Skystyr, Skytene, and Skyplen, offer solutions for a wide range of applications.

In addition to plastics, PreZero also operates in aluminum and glass recycling, ensuring that these materials are reintroduced into the production cycle without compromising quality. The company leverages its extensive waste management infrastructure to support sustainable supply chains, reduce carbon footprints, and align with regulations promoting the use of recycled materials.

PreZero now operates approximately 460 locations across 11 countries, employs around 30,000 people, and manages a fleet of over 12,200 vehicles. PreZero continues to develop its capabilities in waste management and recycling, offering consultation services on recyclability, sustainable packaging design, and compliance with legal standards for recycled products.

TriPlast [118]

TriPlast is a modern plastic sorting facility situated in Enns, Upper Austria, established through a joint venture between ARA (Altstoff Recycling Austria AG), Bernegger GmbH, and Der Grüne Punkt Holding. The facility, which has a sorting capacity of 100,000 tonnes per year, accounts for 50% of Austria's capacity for sorting lightweight packaging, making it one of the largest and most advanced sorting plants in Europe.

The plant is equipped with advanced near-infrared sensor technology and artificial intelligence, which allow for the precise sorting of 24 different types of materials. This technology ensures that raw materials are prepared for recycling without significant loss of quality. Additionally, the facility operates using energy generated on-site and features a logistics system with a direct railway connection, supporting low-emission transport.

With an investment of more than 65 million euros, TriPlast contributes to Austria's goal of doubling plastic packaging recycling by 2025, while also providing secondary raw materials for the Austrian industry. The facility's location at Ennshafen offers trimodal connectivity via road, rail, and ship, enabling efficient and climate-friendly transport of materials. The plant's technological capabilities support Austria's efforts to meet EU recycling targets and reduce reliance on virgin raw materials.

Creacycle /Creasolve [119]

CreaCycle GmbH, based in Germany, is specialized in unlocking the value of plastic waste through its innovative CreaSolv Process, a solvent-based technology that allows for the separation, cleaning, and reuse of polymers. By preserving the integrity of polymer chains, this process enables the recycled materials to be reused in their original applications. Since its inception with a feasibility study in 2001, CreaCycle has partnered with the Fraunhofer Institute to develop and refine this technology, offering a comprehensive service for plastic recycling projects. The company aims to support the transition to a circular economy by providing solutions that meet the growing demand for high-quality polymer recyclates. One special focus of that technology is the decontamination of recycled plastic through separation of the polymers from additives.

PureCycle [120]

PureCycle is claiming to revolutionize the way polypropylene (PP) plastic waste is recycled, addressing a critical gap in the plastic recycling industry. PP is one of the most commonly used plastics, found in everything from food packaging to automotive parts, yet it has historically been difficult to recycle effectively. PureCycle's innovative purification process is aiming to change this by removing contaminants, colours, and odours, resulting in a recycled plastic that should be nearly indistinguishable from new material. This ultra-pure recycled resin can be reused in a wide variety of applications, creating a closed-loop system that reduces reliance on virgin plastics.

Polystyvert [121]

Polystyvert has developed a proprietary technology for recycling all types of polystyrene—expanded, extruded, and injection-moulded—using a dissolution process with an essential oil. This safe and efficient process rapidly dissolves polystyrene, allowing for the removal of contaminants through coarse filtration and the production of high-quality, pelletized recycled polystyrene. The recycled material retains the properties of virgin polystyrene and can be used in various applications, including insulation panels and food trays. Polystyvert's technology supports a circular economy for polystyrene by enabling the regeneration of both expanded and high-impact polystyrene, reducing reliance on fossil fuels and preventing waste. Polystyvert, has recently announced the closing of a first tranche of a Series B funding round, securing over $16 million. This significant investment marks a crucial step towards the construction of its first commercial plant in Montréal, Québec, which will be dedicated to recycling highly contaminated polystyrene waste. The funding is sourced from both European and North American investors. By advancing towards the deployment of this plant, Polystyvert aims to scale its innovative solution globally through strategic licensing partnerships, further contributing to the sustainable management of polystyrene and ABS plastics.

Polyloop [122]

Polyloop is a French company and specialized in developing compact and user-friendly recycling solutions for complex plastic waste, particularly PVC composite materials. Utilizing a patented STRAP process, Polyloop's technology integrates physico-chemical recycling directly into industrial processes based on a containerized modular smart factory solution.

The company is claiming that this approach allows for the efficient separation and recovery of materials in small, containerized units. These units are designed for decentralized recycling, making them easily deployable on-site, minimizing the need for transporting waste. The company's innovative recycling process, which includes batch dissolution, filtration, and precipitation, enables the recycling of previously non-recyclable composite plastics, offering an effective solution for industries dealing with post-industrial, pre-consumer, or end-of-life waste.

Polyloop was seeking investors for a financing round in 2021, the deployment of modularized plants was intended to be done in 2022. Based on the website it is not clear whether and to what extent they are still operative resp. successful in the market introduction of their solution.

Trashcon [98]

This is an Indian enterprise that developed world's first (patented) completely automated mixed municipal waste segregation system – TrashBot.

The aim is to address mixed municipal waste and to separate it into a biodegradable, wet fraction and a dry waste fraction – mainly plastic – that is used to produce furniture, boards and similar products.

Selected "chemical recycling" technologies

Agilyx / Cyclix [123]

Agilyx, established in 2004, specializes in the chemical recycling of difficult-to-recycle plastics, with a particular focus on polystyrene types such as general-purpose PS (GPPS), high-impact PS (HIPS), and expanded PS (EPS). With over two decades of experience and eight generations of technology, Agilyx claims to be a leader in creating circular pathways for plastics, including mixed waste, polystyrene, and PMMA. The company employs pyrolysis-based thermo-chemical conversion of waste polymers to monomers, a process in which the pyrolysis gas reaction product is quenched and recovered as Agilyx Styrene Oil (ASO). This oil is then further purified using T.EN's (Technip Energies) technology to achieve a 99.8% pure styrene monomer, which serves as a high-quality feedstock for new polymer production.

Agilyx's patented technologies utilize a catalyst-free, electrified reactor system that reduces carbon impact by integrating renewable energy sources. Their offerings include licensing for proprietary conversion technologies through products like Plastyx™ and Trustyrenyx™, along with equipment supply, technical collaborations, and commissioning services. Through its joint venture, Cyclyx, Agilyx also provides comprehensive feedstock sourcing and management solutions, reflecting a strategic business shift between Cyclixand Agilyx. The company aims to expand global plastic recycling by integrating chemical and mechanical recycling processes to support a low-carbon economy.

Plastic Energy [124]

Plastic Energy is a London-based company focused on addressing global plastic waste challenges through advanced recycling technology. Founded in 2011, the company utilizes its patented TAC™ technology, based on pyrolysis, to convert end-of-life plastics into TACOIL™, a recycled oil that can replace fossil fuels in the production of new plastics. This process helps reduce reliance on landfills and incineration while supporting a circular economy for plastics.

Plastic Energy operates a network of recycling plants across Europe and maintains strategic partnerships with international organizations and governments in North America and Asia. The company's facilities include operations in Spain, the Netherlands, and France, and it has recently expanded its capabilities with new research and development labs at Loughborough University.

In a significant development, Plastic Energy has entered into a memorandum of understanding with INEOS Olefins & Polymers Europe to establish a major new plant in Köln, Germany. This facility will be the largest deployment of Plastic Energy's technology, producing 100,000 tonnes per annum of recycled raw materials from plastic waste. These materials will support the production of essential plastic items for demanding applications, such as food contact and medical uses, and contribute to the transition to a circular economy. It is planned that this plant starts operation in the year 2026.

The agreement with INEOS reflects Plastic Energy's ongoing commitment to innovation and global collaboration in sustainable recycling practices. With a workforce of around 200 employees, Plastic Energy continues to advance its mission of transforming plastic waste management and contributing to a more sustainable future.

SynCycle [125]

SynCycle is an Austrian company specializing in chemical plastic recycling, offering a sustainable solution to the global plastic waste crisis. By transforming non-recyclable plastic into valuable new products, SynCycle contributes to a circular economy and reduces the environmental impact of plastic pollution. SynCycle's proprietary technology involves a multi-step process. First, mixed plastic waste is collected, sorted, and pre-treated to remove contaminants. Then, the prepared plastic is subjected to high temperatures in a pyrolysis reactor, breaking down the polymers into shorter hydrocarbon chains. The resulting pyrolysis gas is converted into a valuable liquid product, known as circular oil, through a condensation process. Finally, the circular oil is further refined to meet specific quality standards, making it suitable for use as a feedstock in the chemical and plastic industries. The company is claiming that SynCycle's technology offers several benefits. It diversifies the plastic value chain, enhances economic viability, reduces dependence on fossil fuels, and improves environmental sustainability. The process is highly efficient, versatile, scalable, and modular, making it adaptable to various feedstock sources and operational requirements.

SynCycle has formed strategic partnerships with industry leaders, including BDI BioEnergy International and the Next Generation Group, to leverage their expertise and resources. These collaborations enable SynCycle to offer a comprehensive solution for chemical plastic recycling, from feedstock preparation to product refinement

Pryme [126]

Pryme BV is a forward-thinking cleantech company dedicated to transforming plastic waste into valuable products through industrial-scale chemical recycling. Their technology, built on an established pyrolysis process, has been refined and enhanced with unique, proprietary features. Pyrme's fully electrified process is designed to allow to run on 100% renewable energy, reflecting their commitment to a low-carbon, circular plastic economy. The company aims to expand its innovative technology by developing a diverse portfolio of owned and operated plants in partnership with strategic collaborators. Pryme is publicly traded on the Oslo Euronext Growth Exchange.

The first industrial scale plant started it´s operation in Q1/2024 in Rotterdam.

Mura Technology [127]

Mura Technology is claiming to be at the forefront of advanced plastic recycling with its proprietary Hydro-PRT (Hydrothermal Plastic Recycling Technology). This innovative process uses supercritical water — water at elevated pressure and temperature — to efficiently break down a wide range of plastic waste, including complex and mixed plastics that are typically challenging to recycle. Unlike traditional methods like pyrolysis, Hydro-PRT produces high-quality hydrocarbons without generating unwanted by-products such as char. The technology is highly scalable, with modular reactors that can be deployed in capacities of 20kt and 50kt, making it adaptable to various industrial needs. Hydro-PRT's output includes valuable liquid hydrocarbons like naphtha and distillate gas oil, which can be used to manufacture new plastics, thereby contributing to a circular economy and reducing reliance on fossil resources. Mura's process not only increases the scope of recyclable plastics but also allows for the endless recycling of materials, significantly advancing sustainability in the plastics industry.

The first industrial scale plant is currently constructed on an industrial site in Teesside, England and is to be operational in 2024.

CuRe Technology [128]

CuRe Technology is focused on addressing the global polyester waste crisis by rejuvenating used polyester, including coloured, contaminated, and complex forms that traditional recycling methods cannot handle. Developed in collaboration with partners such as Cumapol, Niaga, DuFor, and Morssinkhof, and supported by NHL Stenden University, CuRe offers a scalable, low-energy solution that purifies and converts used polyester into high-grade rPET, suitable for replacing PET from fossil-derived sources. The technology is already operational at a pilot plant in Emmen in The Netherlands, with plans for further scale-up to create a fully circular polyester chain, enabling endless recycling of polyester products. CuRe Technology seeks global partnerships to expand and enhance their approach, turning polyester waste into a valuable resource.

The technology positions itself in between chemical and material recycling technologies as it addresses poly-condensated polyester waste only that can be broken down easier than polymerized polymers. The first industrial scale plant will be inaugurated in 2025.

Huayin [129]

Huayin, founded in 1993 in China, specializes in manufacturing waste recycling equipment. The company offers solutions for recycling waste plastics, tires, oil sludge, and engine oil. Huayin provides engineering design based on customer requirements, focusing on selecting appropriate technology for various raw materials and capacities. Their manufacturing process involves high-quality materials and precision engineering, with a strong emphasis on durability and reliability. Huayin's equipment includes systems for pyrolysis, which converts waste plastics into liquid fuel oil, carbon black, and syngas. The company supports global clients with installation, training, and maintenance services. Huayin also provides customization options to meet local environmental standards and specific processing needs.

HVO Swiss [130]

HVO SA, a Swiss-based company, is aiming to improve waste management and energy diversification by converting non-recyclable plastics into biofuels and renewable products. Specializing in the pyrolysis of plastics, HVO utilizes a low-temperature thermal decomposition process to break down plastic macromolecules into smaller, valuable components. This process yields high-energy liquid products that can be refined into ethylene, propylene, and aromatic compounds, essential for industries such as plastics, cosmetics, and solvents. Additionally, the remaining liquid can be transformed into diesel and gasoline, known as "refuel". HVO's innovative technology allows the treatment of various difficult-to-recycle plastics in a single pyrolysis operation, distinguishing it from conventional high-temperature methods that primarily produce gas. HVO Swiss claims that by implementing smart industry 4.0 technologies, HVO enhances the efficiency, quality, and control of the pyrolysis process through interconnected, autonomous systems and AI-driven optimization. The technology supports multiple refining scenarios tailored to produce specific end products, including fuels and chemical intermediates.

Ioniqa Technologies [131]

Ioniqa Technologies is a clean-tech spinoff from Eindhoven University of Technology, specializing in transforming PET waste into high-quality, virgin-grade PET through its proprietary circular technology. IONIQA claims, that their depolymerisation process can recycle all types and colours of PET, including those previously deemed unrecyclable, into food-safe, clear PET bottles. With a scalable platform technology, Ioniqa aims to extend its upcycling innovations to other plastics and organic materials. Currently, they are scaling up a 10,000-tonnes PET recycling plant in the Netherlands that has been operating since 2019 and plan to license their technology globally, addressing the need for sustainable, high-quality recycled plastics.

Carboliq [132]

CARBOLIQ is atechnology platform owned by RECENSO GmbH, Südpack Holding GmbH and Cycle Investment BV and offers a one-stage process for liquefying solid hydrocarbons, combining thermal, catalytic, and mechanochemical mechanisms to convert plastic waste into high-quality liquid hydrocarbons. According to CARBOLIQ the process is operating at atmospheric pressure and below 400°C, and that the CARBOLIQ process efficiently handles mixed and contaminated plastics, yielding a Circular Liquid Resource (CLR) suitable for producing virgin-quality polymers. The system, demonstrated at the ECOWEST disposal center in Germany, operates continuously and has been certified under ISCC-Plus for sustainability. CARBOLIQ's CLR is registered with the European Chemicals Agency (ECHA) and is in the process of market approval as an "Intermediate." The technology aims to close the loop on hydrocarbons and advance the circular economy for plastics.

Licella [133]

Licella is an Australian company which is very active in advanced recycling of plastic waste, specializing in the patented Cat-HTR platform for hydrothermal liquefaction (HTL). LICELLA claims that this technology processes a wide range of natural and man-made polymers, including mixed and multilayer plastics, into high-value, low-carbon products. By converting waste biomass and end-of-life plastics into valuable oil, Cat-HTR supports a circular economy and reduces reliance on fossil resources. Compared to pyrolysis and gasification, Cat-HTR is according to LICELLA more energy-efficient and capable of producing food-grade products. With over 16 years of development, LICELLA has already a long track record in advanced recycling, and operation of commercial plants globally and is partnering with industry leaders to advance a sustainable, low-carbon future.

In the commercialization Licella collaborates with Mura Technologies and Arbios Biotech.

Quantafuel [134]

Quantafuel operates the world's first commercial chemical recycling plant for plastic waste in Skive, Denmark. This pioneering facility processes 20,000 tonnes of mixed plastic waste annually, converting it into liquid products through pyrolysis. These products are then shipped to BASF for upgrading into new plastic products and chemicals, supporting a circular economy. Quantafuel's technology, which purifies and catalyzes the pyrolysis gas, enables the recycling of contaminated and mixed plastics, producing high-quality, chemically recycled materials. The company, based in Oslo, is expanding its operations across Europe, driven by demand for recycled materials and a commitment to sustainability.

Biofabrik [135]

Biofabrik's WASTX Plastic technology employs advanced pyrolysis to convert plastic waste into three primary outputs: green oil, energy-rich gas, and carbon ash. The system features modular design and scalability, processing between 2.5 to 200 tonnes of waste per day. It operates at atmospheric pressure and temperatures up to 500°C, using friction-based energy input for efficient conversion.

According to BIOFABRIK, the technology integrates a compact, containerized setup, allowing for flexible installation and global deployment. The green oil produced can be used as a feedstock for new plastic manufacturing or as an energy source, while the energy-rich gas and carbon ash can be traded or utilized in the production process. BIOFABRIK collaborates with global petrochemical industries to market these outputs, emphasizing a decentralized approach to reduce CO_2 emissions associated with waste management and production.

Plastic2Oil [136]

Plastic2Oil is a clean energy company that develops technology for converting waste plastic into liquid fuels and processing dirty fuels into clean diesel. The company's patented Plastic2Oil (P2O) process is designed to recycle unwashed, unsorted waste plastics, such as polyethylene and polypropylene, into fuels like diesel and naphtha. The P2O technology features a modular, self-cleaning processor that operates with minimal external energy and uses its off-gases for fuel. The process yields a conversion ratio of approximately 86%, with emissions that are within regulatory limits, according to Plastic2Oil. The company's focus is on providing a commercially viable and environmentally sustainable solution for managing waste plastics, reducing reliance on landfills and incineration, and contributing to the production of cleaner fuels.

It seems based on a detailed research that this provider is not operative anymore.

Pyrowave [137]

Pyrowave is a pioneering company in the electrification of chemical recycling processes, focusing on the sustainable transformation of polystyrene waste into valuable raw materials. At the core of Pyrowave's innovation is the PW6 modular technology platform, which utilizes advanced microwave technology to depolymerize polystyrene back into its original monomers. The company claims that this process ensures that the resulting styrene monomers are of a purity comparable to virgin materials and significantly reduces the environmental impact of recycling.

The PW6 platform is designed to be both modular and scalable, making it adaptable to various waste processing capacities depending on local requirements. Pyrowave's claims that its technology operates without the need for solvents or water, further reducing its environmental footprint. The innovative use of microwaves breaks down the polymer chains into monomers, a process known as depolymerization. These monomers are subsequently purified to meet industry specifications and can be reprocessed into virgin-quality resins. The recycled styrene can be used to manufacture a wide range of products, including polystyrene, synthetic rubber, latex, and various plastics for electronic products.

IQ Energy Australia [138]

IQ Energy Australia specializes in providing modular, advanced thermal treatment technologies for plastic waste conversion. Their systems are designed to be highly automated and easy to maintain, featuring compact and heavy-duty construction suitable for harsh environments. The units are transportable and can be integrated either centrally or decentrally, offering flexibility for diverse operational contexts. These units address the challenge of plastic waste by processing it on-site, thereby reducing waste footprint, odour, noise, and the environmental impact of transport. They utilize advanced technology to convert plastic waste into valuable resources such as plastic-derived crude oil, renewable gases, or other products useful in various industries. The systems feature an 'E-skid' for emissions control, ensuring negligible emissions during operation. The technology includes smart device controls via satellite and a user-friendly digital PLC interface, enabling remote management and monitoring. The company claims that this design provides intuitive and consistent operation. Emergency procedures are integrated into the system's programming, and operators do not require extensive technical expertise, as training and support are provided.

Selected "biological recycling" technologies

Carbios [139]

Carbios is pioneering the use of enzymes for the recovery of end-of-life plastics and textiles. It claims to be the first company globally to effectively combine enzymology with plastics, Carbios leverages the specificity of enzymes, a technology traditionally used in industries such as detergents, biofuels, food, textiles, and paper. Carbios' breakthrough lies in applying enzymes for the industrial degradation of plastic polymers and textiles.

The company's research focuses on identifying and optimizing enzymes naturally present in the environment to enhance their polymer degradation activity and heat resistance.

Carbios has successfully developed proprietary enzymes capable of breaking down specific polyesters, particularly PET (polyethylene terephthalate) and PLA (polylactic acid), common in bottles and textiles.

The enzymatic recycling process developed by Carbios involves depolymerizing PET plastics and textiles into monomers, which are then purified and repolymerized into high-quality PET.

At the pilot stage, Carbios' technology has successfully produced the first transparent PET bottles from monomers derived from depolymerized PET plastic and textile waste. The company's industrial demonstration plant, launched in September 2021 at the Michelin Group site in

Clermont-Ferrand, validates the technical, environmental, and economic performance of this enzymatic PET recycling process. This milestone prepares the way for the construction and implementation of the first industrial unit, supported by funding from the European Union’s LIFE Programme, which aligns with the European Commission’s environmental goals.

Samsara Eco [140]

Samsara Eco is an Australian company and claiming to be at the forefront of the enzymatic recycling technology. By harnessing the power of nature, they have developed a process to break down complex plastics into their original building blocks, supporting a circular economy for plastics. The company claims that unlike traditional recycling methods, Samsara Eco's technology can handle a wide range of plastic waste, including contaminated and mixed materials, producing high-quality recycled plastics that can be used to create new products without compromising quality.

The company has made significant strides 2024. A substantial $65 million funding round, backed by prominent investors including Lululemon and Temasek, should help to accelerate the construction of commercial facilities in Southeast Asia. This expansion underscores the company's commitment to scaling its operations and addressing the global plastic waste crisis.

Moreover, Samsara Eco has assembled a Scientific Advisory Board comprised of leading experts in biotechnology and sustainable chemistry. This strategic move reinforces the company's dedication to scientific excellence and innovation. By leveraging the combined expertise of its team and advisory board, Samsara Eco is aiming to revolutionize the plastics industry and deliver a sustainable solution to plastic pollution.

With its technology, substantial funding, and expert leadership, Samsara Eco thinks to be well-positioned to become a global leader in the circular economy.

Protein Evolution [141]

PROTEIN EVOLUTION is a US-based company focused on developing a biological solution to polyester recycling. The company has created a process called Biopure which aims to convert polyester waste into the raw materials needed to produce new polyester. This approach differs from traditional mechanical or chemical recycling methods by offering a potential pathway to create high-quality recycled polyester that is indistinguishable from virgin polyester.

Biopure involves the use of enzymes to break down polyester waste into its constituent components, terephthalic acid (PTA) and mono-ethylene glycol (MEG). These building blocks can then be re-polymerized to produce new polyester. The company positions itself as a potential solution to the challenges of polyester waste management, which currently sees a significant portion of polyester ending up in landfills or incinerators.

By offering a technology that can potentially produce polyester without the use of fossil fuels, Protein Evolution is addressing the environmental concerns associated with polyester production. However, the commercial viability and scalability of the Biopure process, as well as its overall environmental impact, remain to be fully demonstrated.

Comparison matrix of selected plastic recycling and recovery solutions

The following section is showing the complete assessment matrix of the selected plastic recycling and recovery solutions, based on the elaborated assessment parameters, as explained in the **Methodology for comparing plastic recycling solutions.**

Mochamad Satya Oktamalandi

Technology Assessment Matrix

compiled for Catalytic Finance Foundation

1. PRECONDITION aggregation / collection | 2. PRECONDITION sorting according to requirements | 3. recovery | other recovery

key: n.i.a. ... no information available		requirements for the input of the recovery process				process aspects / requirements					
		plastic feedstock security	non-plastic impurities	defined polymers / mixed plastics	preconditioning requirements	technology readiness level	throughput per unit / plant	level of automation	complexity level	decontamination yes/no	additional feedstock
African Solutions	Somalia, Social Business Enterprise	low	sensitive	sensitive	basic preconditioning needed (moisture, polymer type, size, ...) mainly secured by waste pickers.	12	10 kg/h (small machinery, modular set-up)	very low	low	no	sand, stabilizing additives
Bamboo House India	Hyderabad-based social business enterprise, established in 2006	low	sensitive	sensitive	basic preconditioning needed (moisture, polymer type, size, ...) mainly secured by waste pickers.	12	10 kg/h (small machinery, modular set-up)	very low	low	no	no information available
Tufflex Plastics Products (plastic-timber)	Based in Gauteng, South Africa, Tufflex focuses on polyolefin-plastic waste, established 1994, operating a washing plant	high	sensitive	sensitive	preconditioning needed (moisture, polymer type, impurities, size, ...), inhouse capabilities with washing plant; preconditioning mainly secured by waste pickers up-stream	12	100 kg/h	medium	medium	no	no, eventhough tey market their products as plastic-timber, there is no timber in it, it is just products that usually are made out of timber.
Ecopals	addresses polymer modified bitumen to be used for asphalt-production; ecopals receives pre sorted mixed plastic according to specifications and uses combatibilizers to produce polymer-modified bitumen, wherever actually virgin plastic is replaced in asphalt production this practice can be seen as ressource efficient, however additives from mixed plastic waste are not being controlled.	medium	sensitive	rather sensitive; polymer mix according to specifications must be complied with	high; feedstock is mixed plastic waste from plastic sorting plants according to certain specifications that cannot yet be mechanically recycled	12	1 t/h (extrusion process)	high (preconditioning)	high (preconditioning)	no	plastic is used as addition to bitumen and aggregate to produce asphalt
Plazrok	Plazrok™ is manufactured specifically to be a lightweight composite aggregate, made entirely from the waste stream, designed as an additive or a replacement for conventional aggregates for a variety of concrete applications. Plazrok™ not only provides a variety of advantages to concrete but uses all plastic waste without the necessity to sort or separate along side a variety of other waste derived from landfills.	medium; plants can be run in batch mode, modular set-up	robust	robust	low requirements; feedstock is shredded and granulated prior to thermal-mechanical processing (at 160- 220 °C) in the plazrok plant	12	1 t/h	medium	medium	no	90% plastic, 3% PIL master batch and 7% mineral feedstock
DAURULANG	based in Indonesia, Central Java, focusing on receiving mixed plastic with high organic content that is separated and used for vermicomposting	medium	robust	robust	preconditioning and sorting takes place as part of this technological approach	11	0.5 t/h	medium	medium	no	no
Rebrick	based in Indonesia, focuses on the use of rejected plastic and its transformation into building products (bricks)	medium	sensitive	rather robust	preconditioning is mainly done in the collection stage, only defined plastics (multilayer plastics (sachets), plastic bags, bubble wrap, soft plastic / packaging) are used as feedstock.	11	10 kg/h	low	low	no	yes
Trashcon	Indian based company that developed an automated municipal solid waste segregation system. It is focusing on the separation of wet and dry waste and using the shredded dry - mainly plastic- fraction for the production of furniture, flooring, boards and similar products.	medium	robust	robust	none, the preconditioning is done as part of the process	12	various sizes from 0.5 - 12.5 t/h	rather high	rather high	no	no

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CARBON TURNAROUND ambire GLOBAL

Mochamad Satya Oktamalandi

Technology Assessment Matrix

compiled for Catalytic FINANCE FOUNDATION

1. PRECONDITION aggregation / collection
2. PRECONDITION sorting according to requirements
3. recovery
other recovery

key: n.i.a. … no information available	output of the recovery process					sustainability aspects						
	main product of the process	usable by-product	rejects	air emission	product yield per tonne of plastic waste input	circular economy principles	social inclusion / job generation	revenue generation potential	greenhouse gas emission savings / energy aspects	size of product market	environmental aspects (improvement of the impact on air, soil, water (including microplastic generation))	resource efficiency compared with indonesian baseline
African Solutions	tiles, paving stones, fence poles, outdoor furniture	none	none (only usable plastics is used from collection and pre-sorting)	yes, no scrubbing	(>) 1t product yield per t input waste (due to additional feedstock)	downcycling	enabling entrepreneurship	low	positive	high	high	low (no substitution of virgin plastic, but creation of new products)
Bamboo House India	plastic sheets for houses and shelters, utility products from recycled plastic, including mobile phone cases, USB sticks, flower-pots, furniture, and more	none	none (only usable plastics is used from collection and pre-sorting)	yes, no scrubbing	0.5 - 1.0 t	downcycling	enabling entrepreneurship	low	positive	high	high	low (little substitution of virgin plastic, but creation of new products)
Tufflex Plastics Products (plastic-timber)	plastic-timber products (outside furniture, pallets, railway sleepers, sheets, flooring, play-ground equipment,...	none	none, mixed plastic waste is used for plastic-timber products	yes, no scrubbing	0.5 - 1.0 t	downcycling	infrastructure requirement low - medium	medium	positive	high	high	medium (in case of plastic-timber no substitution of virgin plastic, but creation of new products)
Ecopals	polymer-modified bitumen	none	none (only pre-conditioned plastic is used)	n.i.a.	(>) 1t product yield per t input waste (due to additional feedstock)	downcycling	infrastructure requirement medium - high (incl. preconditioning)	high	positive (assessment highly dependent on actual replacement of virgin plastic)	high	high (assessment highly dependent on actual replacement of virgin plastic)	high (assessment highly dependent on actual replacement of virgin plastic)
Plazrok	light-weight aggregate, bricks, sand, ...	none	none	yes, scrubbing in place	(>) 1t product yield per t input waste (due to additional feedstock)	downcycling	infrastructure requirement medium to high	high	positive	high	high (short term); medium (long term)	low (no replacement of virgin plastic, but minerals)
DAURULANG	plastic composite product such as plastic-timber	none	biodegradable organics used for vermicomposting	yes, no scrubbing	0.5 - 1.0 t	downcycling	infrastructure requirement low to medium	medium	positive	medium	high	low (no substitution of virgin plastic, but creation of new products)
Rebrick	pavers, hollow blocks, roof and tile products	none	none (only usable plastics is used from collection and pre-sorting)	no, no scrubbing	(>) 1t product yield per t input waste (due to additional feedstock)	downcycling	infrastructure requirement low to medium	low	positive	high	high	low (no substitution of virgin plastic, but creation of new products)
Trashcon	biodegradable - wet - and non-biodegradable - dry - fraction.	none (except wet fraction for biological treatment)	none (except wet fraction for biological treatment)	n.i.a.	0.5 - 1.0 t	downcycling	infrastructure requirement medium	low	positive	high	high	low (no substitution of virgin plastic, but creation of new products)

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Technology Assessment Matrix

compiled for Catalytic Finance Foundation

key: n.i.a. … no information available					investment aspects					reference
					centralized / decentralized	minimum investment volume per plant (critical size)	CAPEX per tonne treatment capacity	CAPEX per tonne of product output	OPEX per tonne treatment	
1. PRECONDITION aggregation / collection	2. PRECONDITION sorting according to requirements	3. recovery	other recovery	**African Solutions**	decentralized	100 k US-$	1 k US-$	1 k US-$	n.i.a.	https://www.africansolution.so/about-us/
				Bamboo House India	decentralized	100 k US-$	1 k US-$	1 k US-$	n.i.a.	https://www.bamboohouseindia.org/about-us
				Tufflex Plastics Products (plastic-timber)	centralized, industrial scale	100 k US-$	n.i.a.	n.i.a.	n.i.a.	http://tufflex.co.za/
				Ecopals	decentralized	n.i.a. Very much dependent on prior sorting and plastic product used (flake, pellet, …)	n.i.a. Very much dependent on prior sorting and plastic product used (flake, pellet, …)	n.i.a. Very much dependent on prior sorting and plastic product used (flake, pellet, …)	n.i.a. Very much dependent on prior sorting and plastic product used (flake, pellet, …)	https://www.ecopals.de/
				Plazrok	decentralized, small scale, modular	1000 k US-$	50 k US-$	50 k US-$	n.i.a.	https://plazrok.com/
				DAURULANG	decentralized	100 k US-$	appr. 10 k US-$	appr. 4 k US-$/t	low (appr. 800 US $)	daurulang.id
				Rebrick	decentralized and scaleable	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://rebricks.id/
				Trashcon	decentralized	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://trashcon.in/

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1. PRECONDITION aggregation / collection
2. PRECONDITION sorting according to requirements
3. recovery
mechanical recycling & dissolution

key: n.i.a. … no information available		requirements for the input of the recovery process				process aspects / requirements					
		plastic feedstock security	non-plastic impurities	defined polymers / mixed plastics	preconditioning requirements	technology readiness level	throughput per unit / plant	level of automation	complexity level	decontamination yes/no	additional feedstock
Plasticpreneur	equipment provider and know-how transfer oriented enterprise to allow for Social Business Enterprise evolution.	low, low throuput per unit, can be used modular by adding more machines of the same, machine can be turned off and one, according to plastic waste availability	sensitive	sensitive	basic preconditioning needed (moisture, polymer type, size, …) mainly secured by waste pickers.	12	10 kg/h	low	low	no	no
Tufflex Plastics Products (polyolefin pellets)	Based in Gauteng, South Africa, Tufflex focuses on polyolefin-plastic waste, established 1994, operating a washing plant	high	sensitive	sensitive	preconditioning needed (moisture, polymer type, impurities, size, …), inhouse capabilities with washing plant; preconditioning mainly secured by waste pickers up-stream	12	1 t/h	medium	medium	no	no
CreaSolve	dissolution technology, addressing multilayer packaging, brominated plastics, plastics with plastizicers or fibre reinforced plastics; main / most advanced fiel of application is PS-recycling	high	highly sensitive	Thermoplastic polymers (ABS, PS, EPS, PA, PC, PLA, PVC, PET, PE, PP, and blends of these polymers)	sorting by polymer type, shredding and dissolution in tailored CreaSolv® Formulation	10	n.i.a.	very high	high	yes	no
PureCycle	dissolution technology, stock listed company, licenced technology from Proctor & Gamble	high	highly sensitive	PP (90% pure polymer, 10% impurities incl. fillers), NOT mixed waste	high; feedstock is shredded film, granulated fibers or flakes	11	10 t/h	very high	high	yes	no
PolyLoop	french-based company, focussing on PVC recycling, based on website it is not clear whether they are still active, batch process that is developed to be marketed in a containerized solution.	high	highly sensitive	complex plastics, composites, PVC	The material to be recycled is shredded before being inserted into the process. Depending on the type of waste, the extent of upstream separation and cleaning may vary.	8 (decentrallized container-based solution yet to be proven)	100 kg/h	high	high	yes	no
Polystyvert	Canadian based company, Polystyrene is dissolved, the mixture is purified and polystyrene is then separated from the essential oil and pelletized	high	highly sensitive	polystyrene	heavy preconditioning needed in order to get only polystyrene feedstock	9	n.i.a.	high	high	yes	no
Swedish plastic Recycling	Mechanical plastic sorting & recycling plant of the Swedish EPR system on packaging waste with a capacity of 200 ktpy. The sorting plant Site Zero was inaugurated in November 2023. The product is baled plastic goods, that still need to undergo a washing and extrusion stage before they actually can replace virgin plastic.	high	robust	robust	this technology example is capable of providing all pre-conditioning needed for source separated packaging waste to enable closed loop recycling through a subsequent washing and extrusion step.	12	> 10 t/h	very high	very high	no	no
TriPlast	Austrian based plastic sorting plant owned by ARA, Greed.Dot and Bernegger. 100 kt treatment capacitiy, inaugurated in Q2/2024, now Europe´s most advanced plastic sorting plant.	high	robust	robust	this technology example is capable of providing all pre-conditioning needed for source separated packaging waste to enable closed loop recycling through a subsequent washing and extrusion step.	12	> 10 t/h	very high	very high	no	no
PreZero	Large German Waste Management actor owned by the Schwarz Group focussing on the whole plastics material cycle and operating some sorting and recycling plants for plastics across Europe.	high	robust	robust	this example serves the whole plastics material loop for closed loop recycling via mechanical recycling. Prior source separation of packaging waste is a pre-condition.	12	> 10 t/h	very high	very high	no	no

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Technology Assessment Matrix

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key: n.i.a. … no information available

stage	technology	output of the recovery process: main product of the process	usable by-product	rejects	air emission	product yield per tonne of plastic waste input	sustainability aspects: circular economy principles	social inclusion / job generation	revenue generation potential	greenhouse gas emission savings / energy aspects	size of product market	environmental aspects (improvement of the impact on air, soil, water (including microplastic generation))	resource efficiency compared with indonesian baseline
1. PRECONDITION aggregation / collection; 2. PRECONDITION sorting according to requirements; 3. recovery; mechanical recycling & dissolution	**Plasticpreneur**	various plastic product, such as fence poles, pavement stones, hangers, buttons, dishes, ...	none	none (only usable plastics is used from collection and pre-sorting)	an addtional shrubber can be installed in order to protect operators	0.5 - 1.0 t	downcycling	enabling entrepreneurship	medium	positive	high	high	high
	Tufflex Plastics Products (polyolefin pellets)	polyolefin-granulates for injectionand blow-moulding, film, pipe and sheet extrusion	none	none, mixed plastic waste is used for plastic-timber products	yes, no scrubbing	0.5 - 1.0 t	closed loop recycling	infrastructure requirement medium to high	high	high positive	high	high	high
	CreaSolve	clean polymer	none	yes, removed additives/fillers/ reinforcements; amount depending on preconditioning, probably around 20%	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	infrastructure requirement very high	high	high positive	high	high	high
	PureCycle	clean/purified PP resin	none	yes (fillers, impurities, …); amount depending on preconditioning, probably around 20%	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	infrastructure requirement very high	high	high positive	high	high	high
	PolyLoop	PVC resin	none	yes (fillers, impurities, …); amount depending on preconditioning, probably around 20%	no	0.5 - 1.0 t	closed loop recycling	infrastructure requirement medium to high	high	high positive	high	high	high
	Polystyvert	polystyrene pellets	none	yes, removed additives; amount depending on preconditioning	no	0.5 - 1.0 t	closed loop recycling	infrastructure requirement medium to high	high	high positive	high	high	high
	Swedish plastic Recycling	baled plastic goods for washing and recyling stage: rigid PP, rigid HDPE, flexible LDPE, flexible PP, transparent PET trays, transparent PET bottles, coloured PET bottles, EPS, PS, PVC	none	two grades of mixed polyolefin laminates, and metal and non-plastic rejects	no, no extrusion or thermo-chemical conversion on-site	0.5 - 1.0 t	closed loop recycling	infrastructure requirement high	high	high positive	high	high	high
	TriPlast	24 different types of materials, baled plastic goods are subject to subsequent washing and recyling stage	none	metals, fines, non sortable rejects	no, no extrusion or thermo-chemical conversion on-site	0.5 - 1.0 t	closed loop recycling	infrastructure requirement high	high	high positive	high	high	high
	PreZero	various fractions of baled plastic goods for washing and recyling stage	none	metals, fines, non sortable rejects	no, no extrusion or thermo-chemical conversion on-site of the sorting plant, this is done in a subsequent step on other sites.	0.5 - 1.0 t	closed loop recycling	infrastructure requirement high	high	high positive	high	high	high

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Technology Assessment Matrix

compiled for Catalytic FINANCE FOUNDATION

1. PRECONDITION aggregation / collection
2. PRECONDITION sorting according to requirements
3. recovery
mechanical recycling & dissolution

key: n.i.a. … no information available	investment aspects					reference
	centralized / decentralized	minimum investment volume per plant (critical size)	CAPEX per tonne treatment capacity	CAPEX per tonne of product output	OPEX per tonne treatment	
Plasticpreneur	decentralized, small scale	10 k US-$	0.2 k US-$	0.2 k US-$	n.i.a.	https://plasticpreneur.com/
Tufflex Plastics Products (polyolefin pellets)	centralized, industrial scale	1000 k US-$	n.i.a.	n.i.a.	n.i.a.	http://tufflex.co.za/
CreaSolve	centralized, industrial scale	10 M US-$	n.i.a.	n.i.a.	n.i.a.	https://www.creasolv.de
PureCycle	centralized, industrial scale	>50 M US-$	appr. 3 - 4 k US-$/t	appr. 4 k US-$/t	high	https://www.purecycle.com/
PolyLoop	decentralized	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://polyloop.fr/strap-recycling/know-how/?lang=en
Polystyvert	n.i.a.	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://polystyvert.com/
Swedish plastic Recycling	centralized, industrial scale	>50 M US-$	0.5 k US-$	approx. 0.6 k US-$ (based on 90% recovery rate)	n.i.a.	https://www.svenskplastatervinning.se/en/site-zero/
TriPlast	centralized, industrial scale	>50 M US-$	0.7k US-$	n.i.a.	n.i.a.	https://triplast.at/
PreZero	centralized, industrial scale	>50 M US-$	0.7k US-$	n.i.a.	n.i.a.	https://prezero.de/

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Technology Assessment Matrix

compiled for Catalytic FINANCE FOUNDATION

key: n.i.a. … no information available

1. PRECONDITION aggregation / collection
2. PRECONDITION sorting according to requirements
3. recovery
chemical recycling

		requirements for the input of the recovery process				process aspects / requirements					
		plastic feedstock security	non-plastic impurities	defined polymers / mixed plastics	preconditioning requirements	technology readiness level	throughput per unit / plant	level of automation	complexity level	decontamination yes/no	additional feedstock
Agilyx / Cyclyx	originally European-based, now US, joint activity of Exxon Mobile, Lyondell-basell, Braskem and other big corporates	very high	highly sensitive	highly sensitive (PS)	rather high	9 (first Cyclyx Circularity Center to be commissioned in 2025, Greater Houston area. The facility will be designed to produce 150,000 metric tonnes of plastic feedstock per year)	10t/h Cyclyc Circularity Centers @ 178kt/a	very high	very high	yes	no
Plastic Energy	Founded in 2011, headquartered in London. Active in UK, Singapore, Malaysia, Spain, France. Developed a patented pyrolysis process. Plastics are heated in the absence of oxygen to form hydrocarbon vapours. These vapours are then condensed into a recycled oil, called TACOIL™. This technology is focussing on complementing mechanical recycling.	high	sensitive	Mixed pre-sorted post-consumer plastic waste that cannot be mechanically recycled	extensive pre-sorting, shredding	12	1 - 3 t/h scalable	very high	very high	yes	no
Syncycle	Joint technology development from the Austrian technology providers NGE and BDI, which did develop together a decentralized containerized solution for plastic recycling based on pyrolysis.	high	sensitive	mixed polyolefin plastic wastes	extensive pre-sorting, shredding, drying	7	1 t/h	very high	very high	yes	no
PRYME	Dutch company which developed a chemical recycling solution based on pyrolysis on industrial scale. First industrial scale plant inaugurated in Q4/2023 in Rotterdam.	high	sensitive	mixed mainly polyolefin plastic wastes	extensive pre-sorting, shredding	9	10 t/h	very high	very high	yes	no
Mura Technology	British company which developed since 2014 a hydrothermal advanced recycling process, Hydro-PRT, uses supercritical water to recycle waste plastics back into fossil-equivalent feedstocks to make new plastics	high	sensitive	mixed plastic waste, flexible, multi-layered materials	some pre-conditioning such as shredding, metal-separation is done a s part of the process.	8	2.5 t/h	very high	very high	yes	no
CURE Technology	This technology focusses on breaking down polycondenstated polyester according to the 80:20 pareto rule. This type of break down is possible for polyester only and has the advantage that the energy demand of the process is much lower.	high	sensitive	polyester, PET	sorting, washing and preparation	7	20 kg/h	very high	very high	yes	no
Huayin	Chinese producer of pyrolysis plants, since 1993 on the market. Offering solutions for waste tires and waste plastic recycling	high	sensitive	all types of plastics exept PET and PVC	sorting and shredding	12	3 t/h	very high	very high	yes	no
HVOSwiss	Swiss company, pusueing the idea to manufacture boifuel and renewable products from non-recyclable plastics.	high	sensitive	all types of polymer except PET and PVC	plastics must be as clean as possible and shredded into 5 cm pieces.	9	different sizes from 50 kg/h up to 600 kg/h	very high	very high	no	no
IONIQA	Spinoff from the Eindhoven University of Technology (NL), developed a plastic recycling solution for PET (could be applied in the future for other polymers too). Technology used is based on depolymerisation and filtration.	high	sensitive	PET (coloured)	sorting, washing and preparation	9	1 t/h	very high	very high	yes	no

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Technology Assessment Matrix

compiled for Catalytic FINANCE FOUNDATION

key: n.i.a. … no information available		output of the recovery process					sustainability aspects						
		main product of the process	usable by-product	rejects	air emission	product yield per tonne of plastic waste input	circular economy principles	social inclusion / job generation	revenue generation potential	greenhouse gas emission savings / energy aspects	size of product market	environmental aspects (improvement of the impact on air, soil, water (including microplastic generation))	resource efficiency compared with Indonesian baseline
1. PRECONDITION aggregation / collection; 2. PRECONDITION sorting according to requirements; 3. recovery; chemical recycling	Agilyx / Cyclyx	styrene monomer	none	yes; amount depending on preconditioning	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
	Plastic Energy	TACOIL™ (pyrolysis oil) as feedstock for refineries	none	yes; amount depending on preconditioning	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
	Syncycle	heavy (POH) and light pyrolysis oil (POL)	syngas	yes; amount depending on preconditioning	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
	PRYME	pyrolysis oil for further processing in refineries	none	yes; amount depending on preconditioning	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
	Mura Technology	naphta, destillate gas oil, heavy gas oil and heavy wax residue	none	yes; amount depending on preconditioning	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
	CURE Technology	PET, Polyester	none	yes; amount depending on preconditioning	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
	Huayin	pyrolysis oil for energy generation or as feedstock for refineries.	syngas that can be used for heating purposes, carbon black	yes; amount depending on preconditioning	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
	HVOSwiss	diesel, kerosene, naphtha, gasoline	none	none	n.i.a.	0.5 - 1.0 t	downcycling if fuel is combusted	no, not the primary focus	high	positive	high	high	low, if fuel combustion is aimed at
	IONIQA	monomer BHET	none	yes; amount depending on preconditioning	n.i.a.	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high

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key: n.i.a. ... no information available		investment aspects					reference
		centralized / decentralized	minimum investment volume per plant (critical size)	CAPEX per tonne treatment capacity	CAPEX per tonne of product output	OPEX per tonne treatment	
1. PRECONDITION aggregation / collection; 2. PRECONDITION sorting according to requirements; 3. recovery; chemical recycling	Agilyx / Cyclyx	centralized	>50 M US-$	appr. 0.7 k US-$/t	appr. 0.8 k US-$/t	high	https://www.agilyx.com/ https://10to90.com/cyclyx/
	Plastic Energy	industrial scale, scalable decentralized plants	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://plasticenergy.com/
	Syncycle	industrial scale, scalable decentralized plants	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://www.syncycle.com/
	PRYME	centralized, industrial scale	40 M US-$	1 k US-$	appr. 0.9 k US-$	n.i.a.	https://pryme-cleantech.com/technology
	Mura Technology	centralized, industrial scale	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://muratechnology.com/
	CURE Technology	centralized, industrial scale	30 M US-$	1.2 k US-$	n.i.a.	n.i.a.	https://curetechnology.com/
	Huayin	centralized (the company is also offering very small decentralized solutions)	n.i.a.	appr. 0.1 k US-$/t	n.i.a.	n.i.a.	https://www.huayinenergy.com/
	HVOSwiss	decentralized	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://www.hvoswiss.ch/solutions
	IONIQA	centralized, industrial scale	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://ioniqa.com/

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key: n.i.a. … no information available							requirements for the input of the recovery process				process aspects / requirements					
						plastic feedstock security	non-plastic impurities	defined polymers / mixed plastics	preconditioning requirements	technology readiness level	throughput per unit / plant	level of automation	complexity level	decontamination yes/no	additional feedstock
1. PRECONDITION aggregation / collection	2. PRECONDITION sorting according to requirements	3. recovery	chemical recycling	Carboliq	German based company which developed a plastic recycling solution based on liquefying solid hydrocarbons based on depolymerisation technology.	high	sensitive	multilayer co-extruded films are processed (applied to hard plastics as well as foams)	The size of the infeed material is limited to 2D: max. 40mm or 3D: max. 5mm. In general, it has to be free of metals, stones, glass, ceramics and porcelain. Humidity should not exceed 18%.	8	0.6 - 1.0 t/h per module modularized	very high	very high	yes	catalyst
				Licella	Based in Australia. Did develop a patented Cat-HTR™ (Catalytic Hydrothermal Reactor) platform for chemical recycling of plastic. This technology is at the core of the plastic recycling technology offered by MURA Technology.	high	sensitive	mixed end-of-life plastic, mainly polyolefines (including flexible and multilayer plastics)	non-plastic contamination has to be removed, shredding	11	2.5 t/h	very high	very high	yes	water
				Quantafuel	Norwegian technology provider. Did develop a pyrolysis solution for the recycling of plastic.	high	sensitive	tolerates a unique mixture of rigid waste plastics	extensive pre-preparation such as shredding, washing, sorting, extrusion	8	2 - 2.5 t/h	very high	very high	yes	no
				Biofabrik	Biofabrik is a German company founded in 2011, which developed several GreenTech solutions for the global market. Among them scalable small containerized pyrolysis plants for plastic recycling called WASTX Plastic. In 2020 a pilot plant has been commissioned and in 2022 an industrial-scale plant has been inaugurated in Australia.	high	sensitive	post-consumer waste materials such as HDPE, LDPE and PP	after grinding, the substrate is stored in the silo and automatically dosed in order to achieve the best possible processability in the reactor.	12	2.5 - 200 t/d	very high	very high	yes	no
				Pyrowave	Canadian company which uses microwave technology to depolymerize polystyrene back into its original monomers. The continuous process heats and liquifies the plastic. A filter removes inorganic impurities. The processed polystyrene is mixed with silicon carbide particles to interact with a high energy microwave field. Organic contaminants and colour pigments are removed through the microwave heat.	high	sensitive	polystyrene	extensive pre-sorting, shredding	9	0.2 t/h per reactor	very high	very high	yes	no
				IQ-Energy Australia	Australian company who hold a licence for the Asia-Pacific Region for the Canadian, IQ Energy Inc., technology for modular decentralized plastic recycling technology based on pyrolysis. The technology was developed by IQ Energy in Canada.	high	sensitive	mixed plastic waste	extensive pre-sorting, shredding	10	1 t/h	very high	very high	yes	no
			biological recycling	Carbios	French company which did develop one of the first biological recycling solutions based on enzyms for the recycling of all type of PET plastic / Polyester textile waste.	high	sensitive	PET (for PLA based plastics under development)	extensive pre-sorting, shredding	7-8	> 10 t/h	very high	very high	yes	enzyms
				Samsara Eco	Australian biotechnology company which is developing enzyms for degrading different types of plasticwaste into simple monomers for virgin plastic production.	high	robust	can handle hard-to-recycle plastics, contaminated plastics, mixed plastics, and plastics containing additives (like colours)	cold washing, chipping, …	7-8	1 t/h scalable	very high	very high	yes	enzymes & chemicals
				Protein Evolution	US based biotechnology company, founded in 2021, which has created a process called Biopure which aims to convert polyester waste into the raw materials by using enzymes. Enzymes are created by using AI .	high	sensitive	currently just polyester waste	Pretreatment to prepare the polyester plastic waste for the biological recycling	5	n.i.a.	very high	very high	yes	enzymes

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Technology Assessment Matrix

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1. PRECONDITION aggregation / collection
2. PRECONDITION sorting according to requirements
3. recovery

key: n.i.a. ... no information available		output of the recovery process					sustainability aspects						
		main product of the process	usable by-product	rejects	air emission	product yield per tonne of plastic waste input	circular economy principles	social inclusion / job generation	revenue generation potential	greenhouse gas emission savings / energy aspects	size of product market	environmental aspects (improvement of the impact on air, soil, water (including microplastic generation))	resource efficiency compared with indonesian baseline
chemical recycling	Carboliq	mixture of hydrocarbons	minor volumes of gases, e.g burning in a gen-set	condensates	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
chemical recycling	Licella	plasticrude	gas, which is used to power the process	yes; amount depending on preconditioning	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
chemical recycling	Quantafuel	pyrolysis oil for refineries	none	yes; amount depending on preconditioning	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
chemical recycling	Biofabrik	electricity or sale of the pyrolysis oil to the petrochemical industry	pyrolysis gas	yes (residual materials such as ash and coal 30 kg/day from 1000 kg plastic waste input)	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling (if pyrolysis oil is used as new plastic feedstock)	no, not the primary focus	high	positive	high	high	high
chemical recycling	Pyrowave	styrene monomer	pyrolysis gas	yes; amount depending on preconditioning	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
chemical recycling	IQ-Energy Australia	pyrolysis oil for plastic production	none	yes; amount depending on preconditioning	yes, scrubbing in place	0.5 - 1.0 t	closed loop recycling (if pyrolysis oil is used as new plastic feedstock)	no, not the primary focus	high	positive	high	high	high
biological recycling	Carbios	original monomers	none	yes; amount depending on preconditioning	no air emissions	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
biological recycling	Samsara Eco	monomers	none	yes; amount depending on preconditioning	no air emissions	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high
biological recycling	Protein Evolution	monomers	none	yes; amount depending on preconditioning	no air emissions	0.5 - 1.0 t	closed loop recycling	no, not the primary focus	high	positive	high	high	high

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Technology Assessment Matrix

compiled for Catalytic Finance Foundation

key: n.i.a. … no information available					investment aspects					reference
					centralized / decentralized	minimum investment volume per plant (critical size)	CAPEX per tonne treatment capacity	CAPEX per tonne of product output	OPEX per tonne treatment	
1. PRECONDITION aggregation / collection	2. PRECONDITION sorting according to requirements	3. recovery	chemical recycling	Carboliq	centralized, industrial scale	15 M US-$	1.5 k US-$	1.7 k US-$	<400 US-$	https://www.carboliq.com/
				Licella	centralized, industrial scale	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://www.licella.com/
				Quantafuel	centralized, industrial scale	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://www.quantafuel.com/
				Biofabrik	decentralized and scaleable containerized plant	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://biofabrik.com/de/wastx-plastic/
				Pyrowave	centralized, industrial scale	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://www.pyrowave.com/en/microwave-technology
				IQ-Energy Australia	decentralized and scaleable containerized plant	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://iq-energy.com.au/our-technologies/
			biological recycling	Carbios	centralized	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://www.carbios.com/
				Samsara Eco	centralized	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://www.samsaraeco.com/
				Protein Evolution	centralized	n.i.a.	n.i.a.	n.i.a.	n.i.a.	https://www.protein-evolution.com/

Concluding remarks to technology comparison

When comparing plastic recycling technologies, several key factors emerge as critical in determining the effectiveness of recycling systems. One of the most fundamental is the **collection coverage as well as the type of collection**. In regions where formal waste collection systems are lacking, informal actors play a dominant role, focusing primarily on rigid plastics with a higher mass-to-volume ratio to maximize financial returns. Consequently, lower-value plastics often remain unmanaged, highlighting the importance of broad and inclusive collection mechanisms to increase recycling rates across all plastic types.

Another essential consideration is the necessity of **pre-conditioning** waste to meet the specific process requirements of different recycling technologies. Whether manual or automated, pre-conditioning ensures that quality input is available for recycling and can vary in complexity based on the region's financial and social context. In areas with low labour costs and a focus on social inclusion, manual sorting may be viable, while more developed regions might favour advanced automated facilities to enhance efficiency and output quality. If decisions are made regarding the implementation of a specific recycling solution the collection stage as well as the pre-conditioning required need to be considered as well as these aspects might have a prohibitive effect for specific technologies due to non-availability of feedstock or non-functioning of the recycling process.

The **distinction between open-loop and closed-loop recycling technologies** also complicates direct comparisons. Closed-loop recycling aims to keep plastics within the plastic value chain, allowing for multiple recycling cycles. In contrast, open-loop recycling repurposes plastics as substitutes for other materials, such as sand or gravel, often resulting in products that are not intended to return to the plastic cycle. Open-loop recycling technologies may serve as "bridging technologies" that provide temporary solutions, particularly in applications where the recycled product is not subject to significant wear and tear and can potentially be reintegrated into the plastic cycle at its end of life.

Moreover, open-loop recycling tends to require lower-quality input materials and is often better suited for areas with limited waste management infrastructure. In contrast, closed-loop systems demand higher-quality feedstock, necessitating either separate collection systems with extensive sorting or complementary technological setups capable of producing the required feedstock-quality. This reliance on high-quality input underscores the importance of established sorting plants in ensuring the success of closed-loop recycling.

Finally, while open-loop or down-cycling methods may offer immediate solutions for managing plastic waste at lower costs, they pose long-term challenges for the development of closed-loop systems in a given region. By diverting plastics away from the plastics value chain, these technologies hinder efforts to build sustainable recycling systems that keep materials within the cycle for multiple uses. As a result, balancing the need for immediate waste management solutions with the long-term goal of creating a circular plastic economy is a crucial consideration in selecting and implementing recycling technologies.

List of abbreviations

2D	2-dimensional, flexible or film

3D	3-dimensional, rigid
ABS	Acrylonitrile Butadiene Styrene
ASO	Agilyx Styrene Oil
BFRs	Brominated Flame Retardants
bio-PE	bio-Polyethylene
bio-PET	bio-Polyethylene Terephthalate
bio-PA	bio-Polyamides
BPA	Bisphenol A
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CH_4	Methane
CLR	Circular Liquid Resource
CO_2	Carbon Dioxide
CSR	Corporate Social Responsibility
ECHA	European Chemicals Agency
EoL	End of Life
EPR	Extended Producer Responsibility
EPS	Expanded Polystyrene
EU	European Union
GHG	Greenhouse Gas
GPPS	General-Purpose Polystyrene
GVL	gamma-valerolactone (solvent)
GTM	Geo Trash Management
H_2O	Water
HDPE	High-Density Polyethylene
HIPS	High-Impact Polystyrene
HIS	Hyperspectral Imaging Spectroscopy
HTL	Hydrothermal Liquefaction
Hydro-PRT	Hydrothermal Plastic Recycling Technology
INC	International Negotiating Committee
IRS	Informal Recycling Sector
IWB	Itinerant waste buyer
LCA	Life Cycle Assessment
LDPE	Low-Density Polyethylene
LDO	Light Diesel Oil
LVP	Low Value Plastics
MEG	Mono-Ethylene Glycol

MLPs	Multi-Layer-Products
MoEF	Ministry of Environment and Forestry
MSW	Municipal Solid Waste
N_2	Nitrogen
NGO	Non-Governmental Organisation
n/a	Not available
NIR	Near-Infrared
NPAP	National Plastic Action Partnership
OPEX	Operational Expenditure
P2F	Plastic to Fuel
P2O	Plastic to Oil
P2P	Plastic to Plastic
PAHs	Polycyclic Aromatic Hydrocarbons
PC	Polycarbonate
PE	Polyethylene
PESO	Petroleum & Explosive Safety Organisation
PET	Polyethylene Terephthalate
PLA	Polylactic Acid
POPs	Persistent Organic Pollutants
PP	Polypropylene
PS	Polystyrene
PTA	Terephthalic Acid
PVC	Polyvinyl Chloride
PVCD	Polyvinylidene Chloride
R&D	Research & Development
RDF	Refuse Derived Fuel
RIC	Resin Identification Coding System
RPL	Recycled Plastic Lumber
SBE	Social Business Enterprise
SHGs	Self-Help Groups
SIPSN	Sistem Informasi Pengelolaan Sampah Nasional
SPEC	Soft Plastics Engineered Commodity
SRF	Solid Recovered Fuel
STRAP	Solvent-Targeted Recovery and Precipitation
T.EN's	Technip Energies
TPD	Tonnes Per Day
TPU	Thermoplastic Polyurethane

TRL	Technology Readiness Level
ULBs	Urban Local Bodies
UV	Ultraviolet
VOCs	Volatile Organic Compounds
WBC	Central Waste Bank
WB	Waste Bank
WBU	Waste Bank Unit

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About the Subnational Climate Fund

The Subnational Climate Fund (SCF) is a global blended finance initiative that aims to invest in and scale mid-sized (5 – 75 M $USD) subnational infrastructure projects in the fields of sustainable energy, waste and sanitation, regenerative agriculture and nature-based solutions in developing countries.

The SCF finances projects with the support of Technical Assistance grants that help mitigate risk and ensure financial and environmental goals are achieved.

For further information about the SCF, visit: www.subnational.finance