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Current State of Chemical Recycling of Plastic Waste: A Focus on the Italian Experience

Lorenzo Maria Cafiero, Doina De Angelis, Letizia Tuccinardi and Riccardo Tuffi *

Department for Sustainability, ENEA—Casaccia Research Centre, Via Anguillarese 301, S. Maria di Galeria, 00123 Rome, Italy; lorenzo.cafiero@enea.it (L.M.C.); doina.deangelis@enea.it (D.D.A.); letizia.tuccinardi@enea.it (L.T.)

* Correspondence: riccardo.tuffi@enea.it; Tel.: +39-0630484335

Abstract: With a value of 400.3 Mt, the global plastics production increased in 2022 with a plus of 2.5 wt% compared to the previous years. Unfortunately, plastic waste is often disposed of inappropriately, causing environmental problems and an avoidable waste of resources. In 2019, the European Circular Economy Action Plan was issued to encourage plastic recycling. Nevertheless, at the end of 2022, post-consumer mechanically recycled plastics in Europe accounted only for 13.2 wt% of the European plastic production (58.8 Mt). Mechanical recycling fails to recycle mixed, partially degraded, or contaminated plastic waste. Then, there is an acute demand for new, efficient, and cost-effective recycling technologies to fill the gap left by mechanical recycling. Chemical recycling is considered a complementary alternative because it can process waste streams composed of heterogenous and difficult plastics. Currently in Europe, around 58.8 kt (0.1 wt%) of plastic production was obtained by chemically recycled plastics, but the road is marked. The Plastic Europe association announces that its members are going to produce 2.8 Mt of chemically recycled plastics by 2030. Mixed plastic waste is the main target, and pyrolysis and gasification, identified as the suitable technologies for its treatment, represent 80 wt% of the planned capacities.

Keywords: plastic waste; chemical recycling; mechanical recycling; pyrolysis; circular economy

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1. Introduction

In 2022, 400.3 Mt of plastic was globally produced [1], and it is estimated that this demand will quadruple by 2050. Plastics are versatile, economic, light, and durable and are therefore used in many different applications (i.e., packaging, transport, building and construction, automotive, clothing, healthcare and medicine, EEE, toys, etc.). Plastics probably represent the most wide-ranging materials, with packaging as the largest market [1]. Three polymers, polyolefins (PE and PP) and PVC, account for the majority (57.9 wt%) of global plastics production, while circular plastics, bio-based, and post-consumer mechanically recycled plastics represent only 9.4 wt% of the world's plastics production, implying that the economic system of plastics continues to be predominantly linear [1]. Furthermore, most of this plastic, being used for packaging, becomes waste very quickly. Regrettably, plastic waste is frequently managed in an unsuitable manner, leading to significant environmental issues and unnecessary depletion of resources. An estimated 320 Mt of plastic was discarded in 2019, landfilled, incinerated, or introduced into terrestrial or marine ecosystems [2]. It is also estimated that the volume of plastics accumulated worldwide since the 1950s (the amount ever produced minus that incinerated) has reached 8.2 Gt, of which only 2.2 Gt remained in use and 6.0 Gt was considered waste [3]. Moreover, the

anthropogenic GHG emissions through the plastics life cycle, including the extraction of petrochemicals, production of virgin polymers and additives, manufacturing of products, and common EoL options consumption, contribute to climate change [4].

In 2022, European plastic production accounted for 58.8 Mt, and the post-consumer mechanically recycled plastics were only 13.2 wt% [5]. In order to contrast the unsustainable EoL of plastic waste, the European Commission has set the following ambitious circularity objectives for these materials: the regulatory targets of the recently revised waste directives are 10 wt% max landfilling of municipal waste by 2035, 50 wt% recycling of plastic packaging by 2025, and 55 wt% by 2030 [6]. The European Commission's Circular Plastics Alliance sets the target of 10 Mt of recycled plastics used in European products by 2025 [7].

With the aim of making the objectives more stringent and to standardize calculation methodologies across European countries, the Commission Implementing Decision (EU) 2019/665 has introduced a new method for calculating the recycling rate from 2022: not anymore "sending to recycling" but "actual recycling". The new calculation point is considered "*where packaging waste materials enter the recycling operation whereby waste is reprocessed into products, materials or substances that are not waste, or the point where waste materials cease to be waste as a result of a preparatory operation before being reprocessed*" [8]. According to the Municipal Waste Report edited by the Italian Institute for Environmental Protection and Research, in Italy, this new calculation method entailed a decrease in plastic packaging recycling rate, from 55.6 wt% (old calculation method) to about 47.2 wt% in 2021 and 48.9 wt% in 2022 (new calculation method) [9,10], making future recycling targets even more difficult to achieve.

However, the use of SRM in mandatory quotas for plastic packaging raises issues with packaging in contact with food, beverages, and pharmaceuticals. These packages require stringent and necessary health safety conditions, which are challenging and frequently impossible to achieve with mechanical recycling.

Indeed, the promotion of utilizing SRM requires consistency across legal frameworks related to waste, products, and chemicals. Within the European Union, several regulatory impediments to a circular economy have been identified. These include inconsistent regulations on waste transformation, the presence of legacy substances that impede SRM adoption, a lack of information on complex waste streams, and varying classifications of hazardous substances as by-products and waste laws. The international harmonization of regulations across these different sectors is essential for building trust in the quality of recycled plastic materials [11,12].

Nowadays, stakeholders agree that the large-scale mechanical recycling technologies are insufficient to address the demands for a sustainable management of plastic waste. This is primarily due to the challenges posed for its treatment by a typical post-consumer plastic waste. Degraded plastics, complex mixtures of incompatible polymers, multilayers, composites, additives, and thermosets often make mechanical recycling impossible. Consequently, it is imperative to implement significant technical enhancements, existing infrastructure modernizations, and a global proliferation of established complementary technologies. These new processes should enable the sustainable treatment of all residual plastic fractions that are not manageable with conventional methods. Technologies falling under the name of chemical recycling represent a positive step towards reducing disposed waste and contributing to a circular economy for plastics, toward the achievement of the European targets. Chemical recycling, also known as feedstock recycling, aims to convert plastic waste into monomers and chemicals that are then used again as raw materials in chemical processes [13]. Furthermore, these technologies enable the removal of additives

and hazardous substances, and their products could be used for the manufacture of food, beverages, and pharmaceuticals packaging.

Obviously, these technological advancements must be orchestrated in harmony with other new or improved waste management strategies, such as the reduction/ban of disposable objects, reuse, eco-design, reinforcing separate collection, refining sorting, encouraging the use of recycled material in new objects and packaging, monitoring, and governance [14].

The objective of this paper is to provide an overview of the current situation of chemical recycling, first highlighting the critical issues of mechanical recycling (always maintaining its enormous importance in the treatment of plastic waste), and then the different advanced technologies are briefly described, highlighting some simple but often misunderstood or underestimated issues. A focus is dedicated to pyrolysis, the most complementary chemical technology to mechanical recycling because of its inherent characteristics. In conclusion, a framework about the presence in Europe and, particularly, in Italy of industrial plants, in operation, under construction, or planned is provided. The potentialities and needs of these technologies for the full development of sustainable, feasible, and cost-efficient chemical recycling value chains are discussed.

2. Mechanical Recycling

In the European waste management hierarchy established by the Waste Framework Directive 2008/98/EC [11], a well-known principle of waste management law and policy, the recycling option follows prevention and reuse, coming before energy recovery and disposal. Currently, when we talk about recycling, we refer to mechanical recycling. Classifications of mechanical recycling depend on the origin of plastic waste. Primary recycling, or closed-loop recycling, recovers the industrial (pre-consumer) waste in the manufacturing process where the plastic is used [15]. Conversely, secondary recycling reprocesses post-consumer waste into new products [16] through several preparatory (e.g., collection/segregation, cleaning, drying, and milling/sizing) and thermo-mechanical phases (e.g., blending/addition, extrusion/injection moulding, and pelletizing). Although both primary and secondary recycling share some process phases, the former preserves the quality of the virgin material, while secondary recycling may result in downcycling due to the partial degradation of plastic properties [17].

Though the incontestable advantages in terms of energy savings, environmental impacts, and GHG emissions, mechanical recycling has some serious limitations, and improving the mechanical recycling rate of plastic waste to reach the European targets will be challenging for many reasons. First, plastic is not a unique material but a big family of different polymers. Many kinds of polymers can be found in each product sector. After that, easily recyclable homogeneous plastics are collected and separated; the residual plastics are a complex mixture of incompatible different polymers and materials (textiles, paper, metals, etc.) that exhibit unpredictable characteristics [18]. Plastics are often filled with substances like glass fibres, colorants, flame retardants, etc., to enhance or to give some specific characteristics [19]. This diversity and lack of standardization hinder mechanical recycling. These complex polymeric mixtures make complete separation and cleaning economically or technically unfeasible. Then, it is evident that the mechanical recycling process is only well-suited for homogeneous and clean polymer streams. Second, polymeric materials undergo irreversible changes due to mechanical, thermal, and oxidative stresses caused by repeated processing and natural aging. Degraded plastics are not suitable for the mechanical recycling. Another issue is that the market for SRM, resulting from recovery/recycling operations of post-consumer waste plastics, is still not properly established. Recycled plastics usage is limited by technological and market factors, and they often underperform compared to virgin plastics. Additionally, high-quality recycled plastics

are difficult to source locally, increasing transport costs. The demand for large quantities of competitively priced recycled plastics that meet strict specifications is challenging. If virgin plastics are economically competitive, manufacturers always prefer them over SRM.

Plastic recycling installed capacities in EU27+3 (EU27+3: European Union Member States, Norway, Switzerland, and the United Kingdom) countries reached 12.5 Mt in 2022. Indeed, this process boasts a well-developed infrastructure across the different EU countries. Around 850 companies were active in recycling plastics in the EU27+3 in the abovementioned year. Predominantly small, these plants have an average capacity of 15 kt/y [20]. Germany, Spain, Italy, the United Kingdom, and France remained the countries with the highest installed capacity in EU27+3, accounting for 60 wt% of the total of 12.5 Mt. They are followed by the Netherlands, Poland, and Belgium (for more details about European performance in plastic waste management, see the reference [5]). PE and PP flexibles hold the largest share of installed recycling capacity compared to other polymers in Spain, Italy, Poland, and Belgium. Additionally, the Netherlands, the United Kingdom, Germany, Spain, and Italy lead in HDPE and PP rigid recycling capacities. Concerning PET, France devotes one-third of its plastics recycling facilities to this polymer, while Germany and Spain dedicate more than one-fourth of their infrastructure to its reprocessing. Regarding the plastic waste streams from ELV and WEEE, France and the United Kingdom hold the highest installed capacities for the treatment of PP, PS, and ABS, among others, whereas Spain holds the highest for PS-EPS [20].

In Italy, over the last decades, mechanical recycling became the first choice for the treatment of plastic waste. It has mostly been limited to packaging waste streams, which are relatively easy to collect and recycle. In 2023, encompassing all operators involved in the recycling processes, Italy produced between 1.3 and 1.45 Mt of post-consumer recycled plastic. Mechanical recyclers contributed to the production of 784 kt of post-consumer plastic in the forms of pellets. This production was dominated by PE (~45 wt%), followed by PET (~25 wt%), MPO (~15 wt%), PP (~10 wt%), and other polymers (about 4 wt%). These fractions are composed of clean, not polluted, mono-polymeric streams that, to be recycled, must have, above all, a consolidated market. Indeed, among the various plastic wastes, PET and HDPE from packaging are routinely recycled, and they have the most profitable economic market as SRM [21]. In the form of irregular scraps, these plastics can be sold at 300–600 €/t [22]. If they are further processed, for example, extruded in regular pellets with certified characteristics, they can be sold at 900–1200 €/t [22]. The technical legislation UNI 10667 sets the Italian standards for recycled plastics, including guidelines for specifying SRM obtained from pre- and post-consumer plastic waste [23].

According to ASSORIMAP, 75 companies engaged in the mechanical recycling of post-consumer plastics account for a total of 84 MRFs distributed across the Italian territory, as reported in Figure 1a [21]. Most of these companies recycle PE film, followed by PET, HDPE, PP, and MPO. There are also recyclers for other polymers such as PS, PVC, EPS, ABS, PA, etc. However, plastic recycling rates remain lower in comparison to those of other materials like paper, metals, and glass (>70 wt%). Most of the recycled plastic was used in the packaging sector (more than 40 wt%, mainly for rigid packaging), followed by the piping sector (12 wt%), and other flexible applications such as waste collection bags (9 wt%). With respect to the previous year, applications in construction and building remained stable at 11 wt%. Household and gardening, agriculture, as well as other sectors, complete the list of applications (Figure 1b) [21].

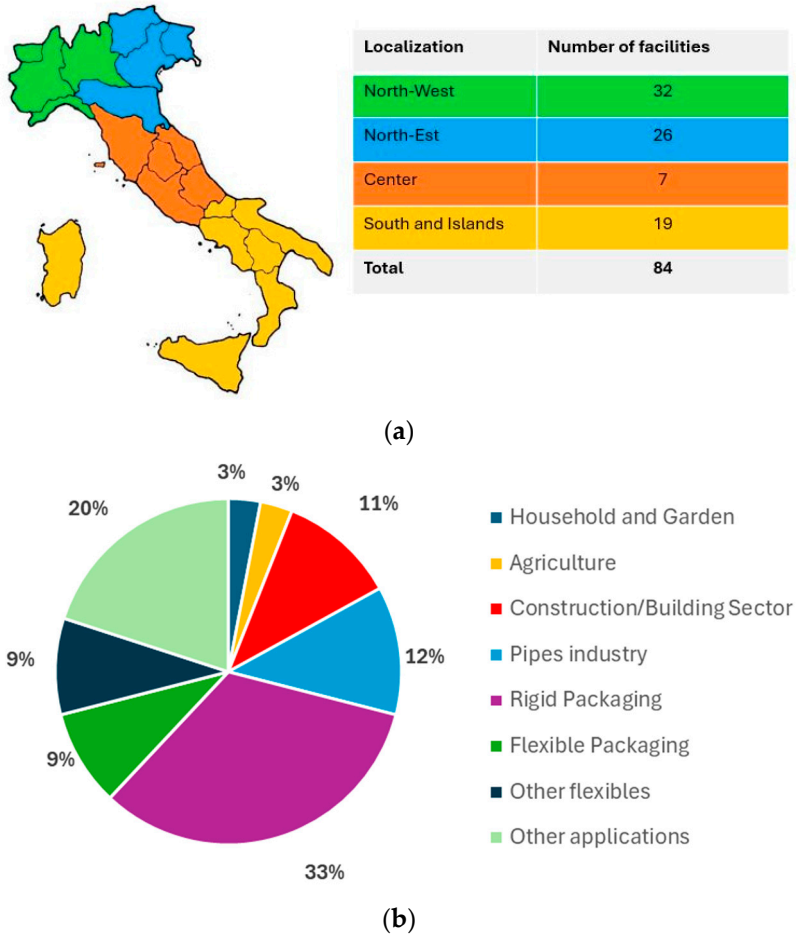


Figure 1. Number of MRFs and localization in Italy (**a**) and uses of post-consumer recycled materials (**b**) [21]. Reproduced with permission from Plastic Consult S.r.l. and ASSORIMAP, Il riciclo meccanico delle materie plastiche REPORT 2023; published by ASSORIMAP, www.plasticconsult.it, 2024.

The plastic residue of MRFs sorting process is probably the most challenging issue of plastic waste management. This residue is a heterogeneous mixture of polluted, intermingled low-value plastics (non-target plastics). In the packaging sector, due to the complexity of plastic packaging and the relative efficiency of the sorting process, a large share of plastics collected for recycling is rejected, accounting for up to ~50 wt% of the input stream [24]. In Germany and the Netherlands, the term DKR-350 (from the Deutsche Kunststoff Recycling technical legislation) defines this residual packaging plastic mixture [25], while in Italy "plasmix" is commonly used by stakeholders. This residue is a mixture of various plastics (not recyclable plastic packaging, sorting process losses, and non-packaging plastics) and, in lower amounts, foreign materials (e.g., paper and cardboard, inert, textile, etc.) [26]. Its composition is variable and depends on the performance of the MRF's sorting process, the quality of the local separate collection, and the market of SRM [27]. More specifically, the plastic fraction of plasmix is composed of MPO (60–70 wt%), followed by PET (4–5 wt%), PS (2–4 wt%), and low amounts of PAs, ABS, XPS, PUs, and others, not always belonging to the packaging sector [24]. In 2023, approximately 500 kt of plasmix output from MFRs, almost the entire amount of which was used for energy recovery: by cement plants as a non-conventional fuel (90 wt%) and by waste-to-energy plants (9.7 wt%). Most of these facilities are installed abroad due to more favourable policies [26]. The improved recovery efficiency of mechanical recycling systems resulted in a significant reduction in the amount of plasmix sent to disposal compared to previous years. Only in 2017 was plasmix defined by a proposed Italian law (still under review) as a suitable material to produce recycled

MPO pellets [28]. In Italy, some pioneering companies have developed strategies for this advanced mechanical recycling. Revet and Montello (capacity of 30 kt/y and 150 kt/y, respectively) operate a hard selection of their plasmix to obtain MPO granules used for the production of garden and street furniture [29]. EcoRevive also produces a certified MPO granule (PlastiQù) for multiple applications in the industrial field (capacity of 4.7 kt/y) [30]. I.Blu (a company of Iren Group) is noteworthy for its production (42 kt/y) of two MPO granules named Blupolymer and BLU-C, the first available in various formulations for use in injection moulding, extrusion, and compounding processes, and the second used as feedstock in chemical recycling processes [31]. I.Blu [32] and Montana [33] (with respective capacities of 165 kt/y and 90 kt/y) produce MPO pellets from plasmix to use as SRA in the metallurgic industry (a discussion of this issue is present in Sections 3.1 and 3.3).

The further residues of these valorization processes of plasmix are other plastic/paper/textile/other materials mixtures with a lower value than the input one that presumably can be only incinerated due to market and facilities limitations [34]. Generally speaking, it can be asserted that the higher the sorting performance of MRFs, the lower the quality of the resulting plasmix (or any residual plastic mixture waste of different product sectors) and the more difficult its further valorization will be.

Given the complexity of plastic waste and the low efficiency of mechanical recycling in many contexts, diversification and innovation in waste treatment technologies are necessary.

3. Chemical Recycling

3.1. Overview

From what has been discussed so far, it is challenging to achieve the European recycling targets or to increase the amount of recycled plastics used in European products by 2025, as recommended by the Circular Plastics Alliance. There is an acute demand for new strategies and actions, but above all, there is a strong demand for new, efficient, and cost-effective recycling technologies to fill the void left by mechanical recycling.

All stakeholders agree that chemical recycling can overcome these limits in the plastics recycling loop, conserve valuable resources, and contribute to the creation of a low-carbon circular economy. For these reasons, nowadays chemical recycling is coming out of universities, research laboratories, and start-ups to enter the world of industry (some experiences are reported elsewhere [35,36]). For the first time in 2023, the plastic obtained from chemical recycling, corresponding to 0.5 wt% of all the circular plastic produced in Europe in 2022, was counted as circular plastic [5].

By the term "chemical recycling", we understand all technologies the aim of which is the attainment of feedstocks, monomers, chemical intermediates, chemicals, and building blocks used one more time as raw material from chemical and petrochemical industries [37]. These products are obtained through the decomposition/conversion/transformation of the chemical structure (so the word "chemical") of the plastic stream of interest.

Products intended to be exploited as fuels are excluded in compliance with the European Waste Framework Directive [11]. In fact, by examining the definition of recycling reported in art. 3, number 17: *'recycling' means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations*. Therefore, the use of a certain technology is not synonymous with chemical recycling. This important aspect is often a source of misunderstanding: it is not the technology that defines chemical recycling but the purpose of the products of these processes. For instance, if a certain mixture of hydrocarbons generated by pyrolysis, defined as "pyrolysis oil", is directly burned for

energy recovery, pyrolysis cannot be included within chemical recycling; conversely, this is allowable if the same mixture is used as a commodity for the petrochemical industry. Furthermore, nowadays, no distinction is made between advanced traffic fuels synthesized from products of chemical recycling technologies and the direct production of heat and electricity. In the endothermic processes, also the amount of products, which are used to satisfy the process energy needs, are excluded by the assessment of the recycling rate. To conclude, recycling is only intended when the outputs of these technologies are conceived to produce new plastics or chemicals. On opposite ends, gasoline can be used as fuel or for the synthesis of rubber, plastics, and solvents, while plastic extruded pellets could be used as fuel, being characterized by high LHVs (20–45 MJ/kg), which are comparable to common fuels [38].

The main compounds for which chemical recycling is conceived are monomers and oligomers to synthesize new polymers. The possibility to obtain monomers with a commercial grade and high yields depends, however, on the characteristics of the feedstock (i.e., heterogeneity, degree of cleanliness, etc.) and, above all, the nature of the starting polymers. Recycled monomers could have a low value on the market that fails to offset the production costs. When monomers are not attractive or attainable, the production of chemicals appears to be the alternative solution. The production of chemicals can also shape up to be a real upcycling, where the process generates higher added value products in comparison to the input materials. The term upcycling is often used improperly in many publications, overlapping the term recycling [39].

Chemical recycling can be roughly divided into solvent-based (chemical) and thermochemical processes in Table 1. Solvent-based processes are more oriented to processing clean streams of plastics, aimed at the formation of monomers, while thermochemical processes are more suitable for processing complex mixtures with the production of chemicals. Some of these technologies can in turn be subdivided into various branches in dependence on the auxiliary energy or the typology of solvent or cleavage agent, additive, or catalyst that are employed. Some technologies are better suited than others to manage a certain kind of plastic waste. Table 2 reports the main products obtained from common plastic waste for the most suited chemical recycling technology, while in Figure 2, the chemical structures of some of these plastics and of their main products after chemical recycling are represented.

Table 1. Classification of chemical recycling technologies with their main characteristics and plastic waste range of application.

Chemical				Thermo-Chemical Processes		
Sub-Categories		**Solvent/Reagent**	**Range of Application**	**Sub-Categories**	**Operating Conditions**	**Range of Application**
Glycolysis		EG	Limited	Pyrolysis	400–900 °C, inert atmosphere	Wide
Methanolysis		Methanol	Limited	Gasification	700–1700 °C, partial oxidative atmosphere	Very wide
Aminolysis		Amine solution	Limited	Hydrocracking	300–500 °C, 30–100 bar	Wide
Hydrolysis	Acid	H_2SO_4, H_3PO_4, HCl, etc.	Limited	Liquefaction *	Subcritical water: 200–300 °C and 10–40 bar	Medium
	Basic	NaOH, KOH, etc.				
	Enzymatic	Enzymes			Supercritical water: T > 378 °C, P > 220 bar	Wide
Ammonolysis		Ammonia solution	Limited			

* Liquefaction can also be carried out by organic solvents, such as acetone, n-hexane, methanol, and ethanol.

Table 2. Exploitable products and suitable processes of chemical recycling associated with thermoplastic materials in terms of quality and yields of products.

Resin	Major Origin of Waste	More Suitable Processes and Main Products		Less or Not Suitable Processes
		Processes	Products	
Mixed plastics	Multilayered plastics, residue of plastic selection (e.g., packaging)	Gasification Pyrolysis	Syngas Crude oil	Solvolysis
PE, PP, and MPO	Household, industrial plastic packaging, agricultural plastics, residue of plastic packaging selection, and automotive	Gasification Pyrolysis Hydrocracking	Syngas Hydrocarbon liquid, waxes, light gases Liquid alkanes, light gases, and lubricants	Solvolysis, HTL
Styrene-based polymers (e.g., PS, ABS, HIPS, SAN, and their mixtures)	WEEE, household and industrial plastic packaging, construction, and demolition	Pyrolysis Hydrocracking	Styrene, styrene oligomers, BTEX, and PAH Monoaromatics	Solvolysis
PET	Household plastic packaging	Hydrolysis Alcoholysis Glycolysis Aminolysis Hydrogenolysis Biocatalysis	EG and TPA DMT and EG BHET and EG TAM and EG BDM and EG BHET, EG, and TPA	Pyrolysis
PA6	Automotive, textile waste, and WEEE	Hydrolysis, basic or acid HTL	ε-Caprolactam, hexamethylene diamine ε-Caprolactam	Pyrolysis
PC	WEEE	Hydrolysis, basic or acid HTL	BPA BPA, phenols	Pyrolysis
PIP	Medical, healthcare, and sport equipment	Hydrocracking	Oil with low content of olefins, aromatics, and coke	Solvolysis
PMMA	Automotive, construction, and demolition, WEEE	Pyrolysis Hydrolysis HTL	MMA MMA MMA	-
PU	Construction, demolition, and automotive	Solvolysis	Di-isocyanate, polyols	Pyrolysis
PVC *	Construction plastic waste	Hydrocracking Pyrolysis, after a dechlorination step	HCl, liquid fuel HCl, aromatics	Solvolysis

* PVC is a critical plastic for chemical recycling technologies, and the best solution appears to be its recovery by dissolution/precipitation methods.

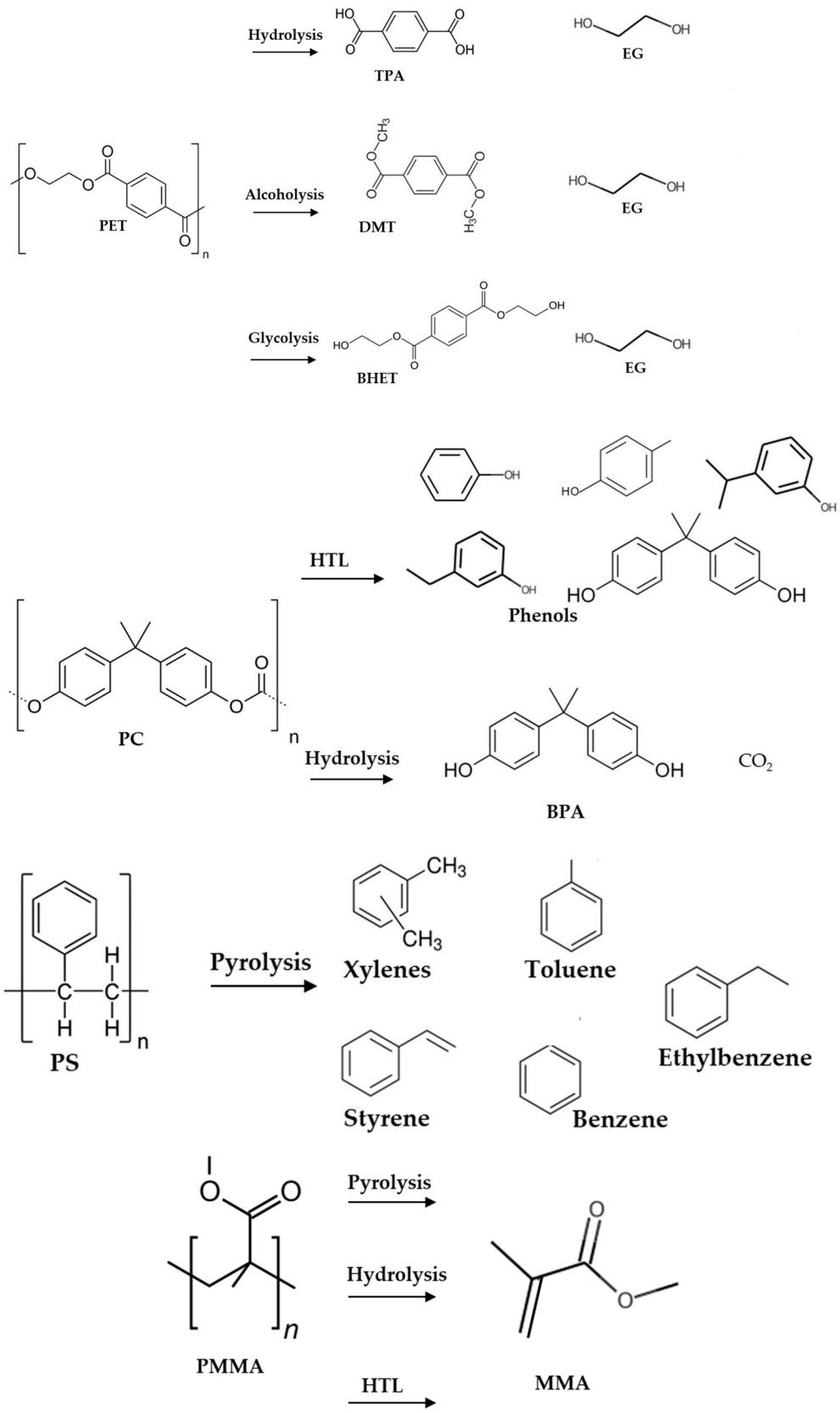


Figure 2. Examples of chemical structures of common plastics and of their main products after chemical recycling strategies discussed in this section and in Table 2.

Solvolysis methods are named after the employed nucleophile type; for instance, water in hydrolysis, ethylene glycol in glycolysis, methanol in methanolysis, amines in aminolysis, and ammonia in ammonolysis [40]. The use of different solvents leads to

different products. Hydrolysis is further divided into acid, basic, neutral, and enzymatic hydrolysis, which uses different aqueous solvents or process conditions. Solvolysis allows obtaining high yields of monomers but cannot be applied to whatever plastic waste, being limited to polycondensation polymers, that is, polyesters, PAs, PCs, PLA, PUs, and acrylate polymers. Practical and interesting results succeeded for PET, PC, Pus, and PAs [35].

Depolymerization via enzymatic catalysis has been pursued as another means to hydrolyse polycondensation polymers. The main target of these processes is PET, which is degraded by microbial enzymatic activity into monomers. The advantage of this technique is that hydrolysis is carried out under mild conditions (30–75 °C and ambient pressure) [41].

When hydrolysis is carried out in sub- or supercritical (i.e., above 378 °C and 210 bar) conditions, it is defined as HTL. HTL usually occurs at 150–400 °C and 220–240 bar, where water becomes apolar, promoting short times of reaction with reference to other hydrolysis processes, that is, with lower times than 1 h and yields above 90 wt%. Other solvents as well can be used in sub- or supercritical conditions.

Pyrolysis (described in Section 3.2) and gasification are the most indicated technologies for the treatment of complex waste. Gasification consists of a partial oxidation carried out by an oxidizing agent (air, oxygen, or steam) kept at an under stoichiometric ratio with respect to the input material, aimed at the production of a syngas enriched in CO and H_2 to be used in a synthesis reaction. This process can treat complex mixtures of plastics so long as the input has been freed from metals and inert materials. It is also required that moisture be kept under a certain threshold and operating temperatures range from 700 to 1700 °C. The syngas that exits the gasification reactor needs to undergo a cleaning phase to achieve a chemical grade. Industrial applications envisage the conversion of syngas into the following alternatives: methanol, olefins, ethanol, and hydrocarbons via a Fischer–Tropsch reaction. The success of gasification depends on the quality of the input and the effectiveness of the cleaning stage. Another viable option that offers interesting commercial outlets is offered by the metallurgical industry. Some metallurgical processes deal with the production of metals from oxides (ore or scraps), where the oxygen is removed through reaction with reducing agents, typically coke or mineral oil [42]. It has been demonstrated on an industrial scale that the plastic fraction in plasmix (and in other plastic-rich waste such as auto shredder residue [43], WEEE [44,45], and even thermosets [45]) provides the required content of carbon and hydrogen to successfully partly replace the traditional reducing agents [42]. A typical scheme envisages that a plastic mixture with an opportune composition is prepared and pelletized or finely pulverized; the pellets or the fine powder are then introduced together with coal or coke into the reducing area of a blast furnace, where they are being gasified at 900–1200 °C generating a syngas that reduces iron ore to iron in the slag bath. This plastic SRA can increase productivity, reduce the coke ratio, decrease the process temperature and, therefore, the energy inputs required, and cut both harmful and CO_2 emissions [46]. Yet only a share of the input plastic feedstock is incorporated in the final iron cast as the remaining share is turned into energy and off-gas [45]. As far as we know, a systematic approach to calculate the recycling rate of SRA is still under discussion.

Hydrocracking is defined as thermal catalytic decomposition in the presence of hydrogen and is mostly known in the scientific literature, while industrial cases are not known. It is applied to single and mixed polymers (polyesters, styrene-based polymers, and polyolefins) and requires a high purity degree of the input stream. It operates between 300 and 500 °C, and the main advantage with respect to traditional pyrolysis consists of the higher quality of the products and the reduction of tars, aromatics, olefins, and heteroatoms [47].

Among these advanced technologies, dissolution can be included as well [41]. Since it does not involve chemical transformations, even if it uses a chemical agent, it is not recognized as a chemical recycling technology, but merely physical. Dissolution is based

on the selection or the development of a suitable solvent to purify or separate a targeted polymer or a valuable additive from the remaining components of the mixed plastic waste. Usually, dissolution is used as a pre-treatment prior to mechanical, mainly, or chemical recycling. Dissolution itself demands a mechanical pre-treatment of the plastic waste stream to be processed, which consists of operations of washing, sieving, density separation, and grinding. In this stage, undesired materials such as textiles, metals, wood, and food residues are removed. Then, the solvent brings into solution the polymer of interest and is afterwards precipitated with the required purity grade by the action of an "antisolvent". With this technique, the integrity of the chemical structure of the polymer is preserved.

Many recycling technologies can cooperate to improve the quality of the final products and the performance of the whole process. Figure 3 shows some examples.

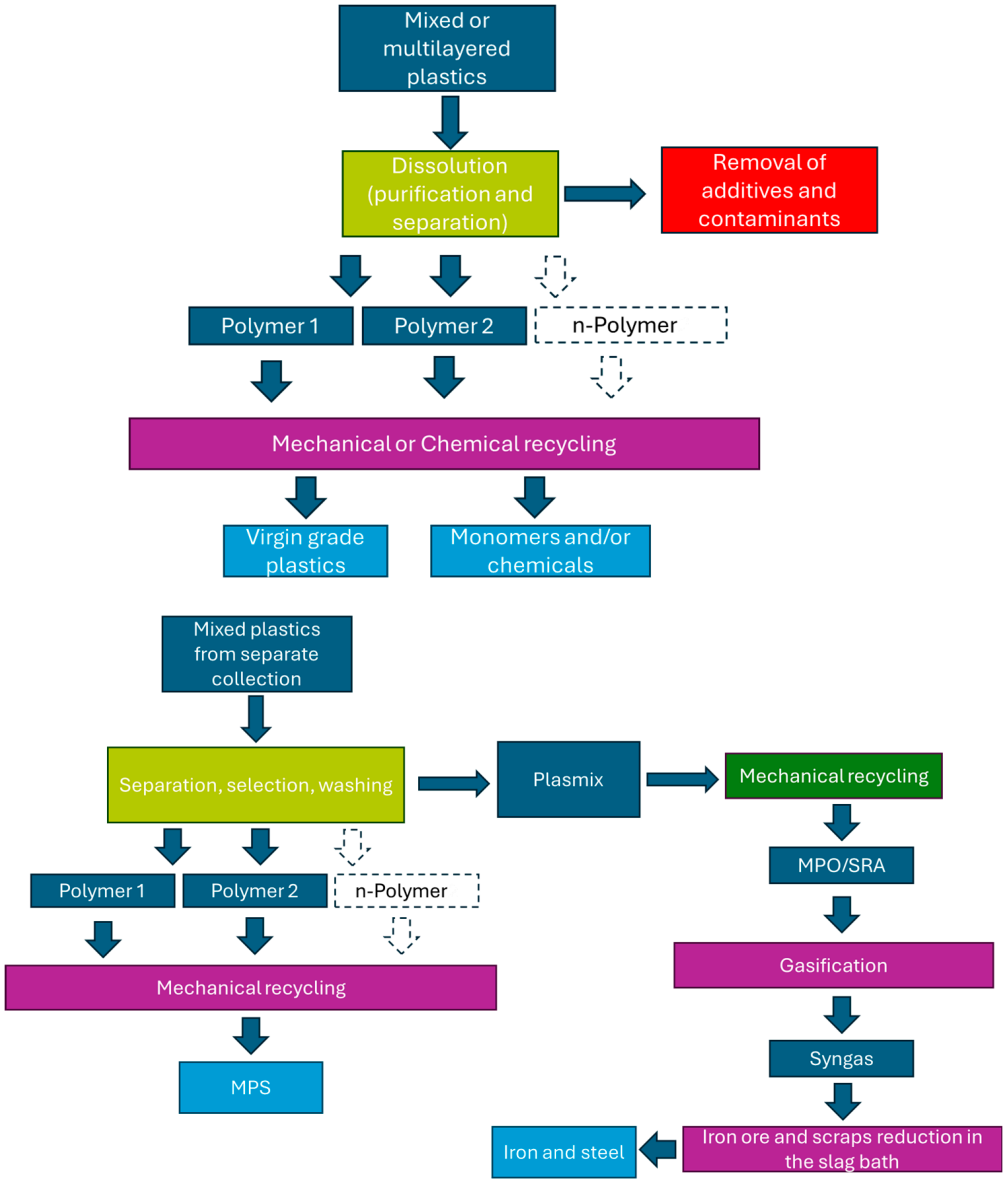


Figure 3. *Cont.*

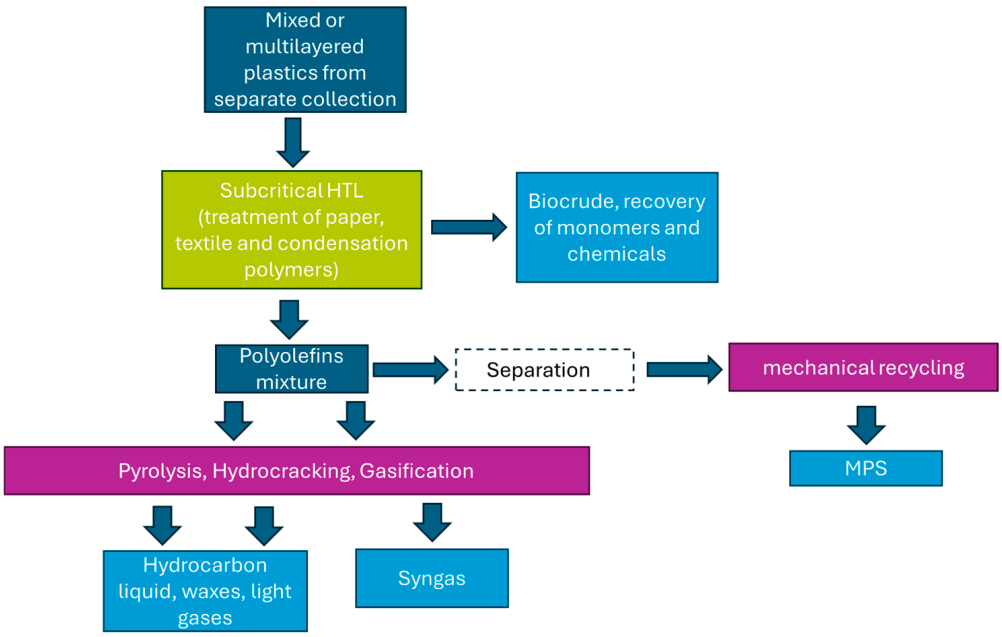


Figure 3. Examples of recycling technologies used in sequence and/or parallel schemes.

Currently, only around 58.8 kt of plastic waste was chemically recycled in Europe in 2022 [1]. A short review of the recent industrial development of these technologies in Europe was reported in Section 3.3.

To conclude, as reported by Vidal et al. [48], a hierarchy of recycling pathways for plastic waste is needed to organize and optimize the carbon recirculation in the system. This hierarchy gives priority to recycling routes that preserve material integrity, value, and chemical structure and that minimize energy and material losses (Figure 4). When a recycling technology must be evaluated for the treatment of a specific waste stream, this hierarchy should be considered before any consideration about the technical and economic feasibility of the process. Mechanical recycling should always be the preferable choice because it is the most sustainable process from many points of view (economic, technological, environmental, etc.). However, mechanical recycling cannot be used to process complex waste [49]. Complex waste requires technologies that minimize the complexity of products (Figure 4). Production plastics offcuts, that is, plastic leftovers following the manufacturing of a set of products, appear intrinsically clean, deprived of any contamination, and therefore provided with a definite composition and consistent quality, and can be converted into pellets or objects with the same polymeric composition (from a simple waste to a complex product). It is not necessary to use dissolution or chemical recycling technologies that would imply a waste of resources and energy. Conversely, it is very complicated to use mechanical recycling or dissolution or hydrolysis on waste as it is, automotive shredder residue, solid recovered fuel, or an undifferentiated urban waste. In these cases, gasification should be evaluated to produce a very simple product as syngas (possibly followed by methanol synthesis) and, at the same time, reduce GHG emissions in comparison to waste-to-energy technologies [50]. Lastly, when recycling technologies fail to yield useful products from the input waste, combustion and energy recovery must be considered as residual options.

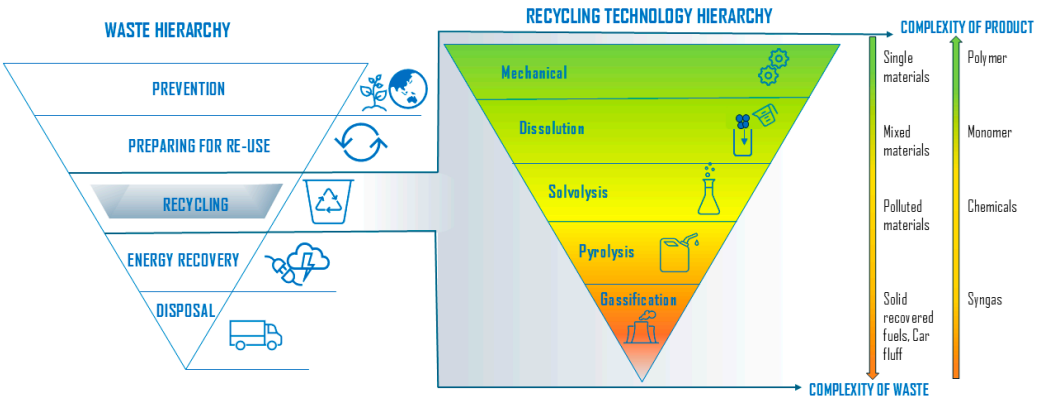


Figure 4. Relation between recycling technologies hierarchy and waste complexity.

Sustainability indexes adopted by the LCA methodology could represent a valid guideline to objectively evaluate the most suitable waste treatment option, as it considers the complexity and chemical physical characteristics of the input material, the scenario where a given technology is supposed to be chosen, and the impacts and interactions played by the technology and the environment. In terms of environmental performance, a study of JRC [51] states that there is not a clear indication that chemical recycling is preferable to other plastic waste management options, such as mechanical recycling or energy recovery. The choice of the management options depends on the type of waste being treated, quality, purity, presence of contaminants, etc. Chemical recycling should be considered a complementary option to other forms of recovery and not the unique solution. The way forward is not to assert the supremacy of one option over another, but to circumscribe what represents the best option in relation to each waste stream, keeping in mind that complex problems need complex solutions.

3.2. Focus on Pyrolysis

One of the most promising chemical recycling technologies is pyrolysis. Pyrolysis is the most researched chemical recycling method for plastics [41]; it was the earliest to be developed [52], and the technology is relatively mature as it has the largest installed input capacity among different advanced recycling technologies in Europe (77 wt%) [53,54].

Pyrolysis is the degradation of organic materials under the effect of heat at a temperature range of 350–800 °C in the absence of oxygen into valuable products or monomers that can be used as feedstock for chemical processes. These products consist of intermediate hydrocarbons in the form of synthetic oil/wax, gas, and carbonaceous solid residue (char). The yields and the compositions of the products depend on the reactor geometry, the presence of a catalyst, the type of plastic material, and the process operating conditions, such as residence time, heating rate, nitrogen flow rate, and temperature [55]. Generally, pyrolysis is considered a versatile technology since, by appropriately manipulating the operating configuration and parameters of the process [56], the process itself can be directed towards the desired product in terms of average compositions and yields. Higher temperatures, as an example, promote cracking reactions with faster kinetics, which result in higher gas yields and lower liquid oil yields. Figure 5 shows an explanatory sketch of the pyrolysis process.

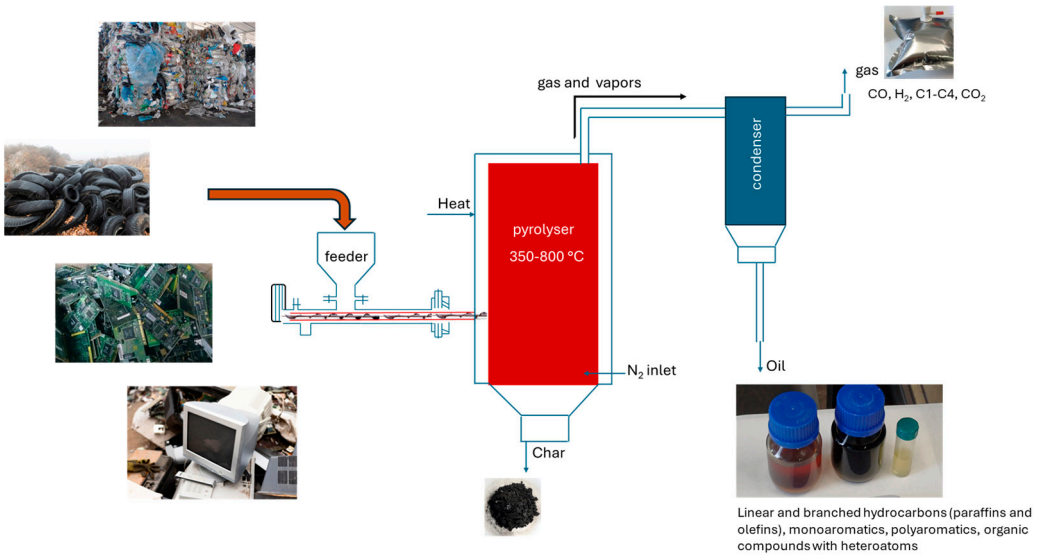


Figure 5. Simplified scheme of pyrolysis process.

The liquid fraction is considered the main product of pyrolysis. A wide spectrum of linear hydrocarbon fragments containing chains of different lengths may be expected in the oil due to the thermal degradation of the polyolefin plastics that occurs through random scission [57]. In particular, these liquid and waxy products, especially if obtained from catalytic pyrolysis [58], after further processing, will ultimately result in petrochemical feedstocks such as naphtha or diesel [59]. In contrast, pyrolysis of PS and styrene-based polymers, PMMA, and polyamides leads to the recovery of a significant portion of the original monomer, exploitable for the synthesis of new plastics. In this case, it refers sometimes to depolymerization (it can be applied only to a high-purity feedstock, at relatively low temperatures) [49]. Pyrolysis of styrene-based polymers also produces high yields of other aromatic compounds such as BTEX [60] that are among the most produced petrochemicals because of their importance as chemical intermediates and building blocks of the chemical industry for the production of solvents, medicines, and polymers, as well as the printing industry and leather tanning. Recent studies show that BTEX can be separated from the pyrolytic oils of aromatic-based polymers, but it can also be selectively produced from tires and polyolefins using appropriate catalysts and operating conditions [54]. PET, PU, and PVC are problematic but usually limited in the typical feedstock mixtures treated by pyrolysis. The pyrolysis of PET yields a gas that mainly consists of carbon dioxide and carbon monoxide, a small amount of liquid, and a significant solid fraction. The high char yield is due to the presence of oxygen atoms and aromatic rings in the polymer structure, responsible for secondary repolymerization reactions [61]. The main products of PET pyrolysis oil are oxygenated compounds, such as benzoic acid, terephthalic acid, aldehydes, acetophenone, dioxolanes, diacetyl benzene, etc. Instead, a relevant amount of polycyclic aromatics is produced at higher temperatures (>700 °C) [62]. Direct pyrolysis cannot be applied to PVC waste due to the generation of chlorinated hydrocarbons, HCl, and harmful emissions. In addition, PVC is not preferred for pyrolysis due to its low liquid yield. However, with proper processing techniques, which include a dechlorination step, PVC can be effectively pyrolysed to yield hydrocarbon-rich products suitable for fuel production or chemical synthesis [39]. PU is characterized by the urethane bond with alternating sequences of soft segments composed of polyester or polyether polyols and hard segments of isocyanates [63]. Consequently, PU pyrolysis is a complex multi-stage degradation process [64] that leads to the formation of di-isocyanates, amines, condensed polyols, and solid residues [64]. Pyrolysis could be considered an unsuitable way for recycling PU; in

fact, the liquid product is extremely viscous and because of its severe instability due to the reactivity of the di-isocyanate component [55]. The other component of thermoplastic PU is either a polyether or a polyester, which could lead to stable pyrolysis liquid with the gasoline and diesel oil boiling fractions composed of the aliphatic polyether/ester fragments, provided that the reactive diisocyanate is eliminated from it either in a lower-temperature pyrolysis step or with the help of an adsorbent [65].

Actually, collected plastic waste of municipal origin is often a mixture of various plastics, and, therefore, the pyrolysis of these feedstocks yields complex mixtures of the abovementioned products. Pyrolysis can be considered a real complementary technology to mechanical recycling because it is more flexible in handling contaminated and heterogeneous post-consumer plastic streams rejected by sorting and mechanical recycling facilities to obtain high value-added products to be used for materials or energy recovery. Pyrolysis could provide a feasible means for recycling when there are low volumes of new materials, and thus separate collection of waste is not yet a cost-efficient option [66]. In fact, only a reduced number of pre-treatment steps is required by pyrolysis, and a low-quality plastic stream (hard-to-recycle plastic waste) can be accepted as feedstock: for example, heterogeneous mixtures, thermosets (impossible to mechanically recycle), composite and laminate materials, deteriorated plastics (for aging, atmospheric agents, or stressed by numerous cycles of mechanical recycling), and contaminated plastics by foreign materials. Because of the lack of knowledge of pyrolysis intrinsic reaction pathways, a quantitative estimation of the entire product dispersion is not possible, but it is obvious that the lower the quality of the plastic waste, the lower the quality of the products [67]. As an example, oils produced from WEEE styrene-based plastics are composed of valuable monoaromatic molecules and problematic compounds such as halogenated ones that must be removed prior to their utilization. Low concentrations of brominated compounds from brominated flame retardants may jeopardize any utilization of the oil [68]. If the main product of pyrolysis is useless, without a clear purpose, basically another waste, and, moreover, energy was spent to obtain it, other kinds of technologies, such as waste to energy, must be considered to manage that input waste.

In terms of carbon neutrality, although the yields of the valuable products are lower in comparison to those of mechanical recycling, pyrolysis offers a sustainable approach to managing plastic waste with several advantages over conventional treatment methods, being essentially the reverse process of manufacturing plastic products from petroleum. The oil and wax obtained from waste plastic pyrolysis are rich in hydrocarbons, which makes them a raw material for a refinery or a petrochemical plant. Indeed, the pyrolysis oil can rarely be used as it is, but it needs to be upgraded and processed in other plants. The typical post-treatment/upgrading processes involve separation steps such as distillation, solvent extraction (or combined processes), and filtration with membrane or chemical processes such as hydrotreating, steam cracking, or catalytic reforming [54]. Hydrogenation processes are mostly required when the plastic feedstock is rich in heteroatoms, being used to remove almost completely contaminants, such as nitrogen, sulphur, oxygen, and metals, from liquid petroleum fractions [69]. In the end, in order to make the pyrolysis process more convenient, it is important to valorize by-products as well. Char is usually considered a waste, but it has a good LHV, and following thermochemical treatments can transform it into a high-value carbon-adsorptive material with an impressive surface area [70]. This feature makes the activated char useful for different applications such as carbon capture, catalyst support, wastewater and waste gas purification, etc. These applications may promote char from a by-product to a main product level. This is important mainly when the chemical structure of some polymers, the use of some catalysts, or the pyrolysis process conditions favour the char formation.

To improve the yields of valuable compounds and the overall quality of the oils produced from these complex plastic wastes, innovative in situ strategies can also be applied. Through catalytic pyrolysis, it is possible to promote the yield of light oil and the production of valuable chemicals to the detriment of heavy oil and undesirable compounds [71]. Depending on their properties such as acidity/basicity and pore structure, catalysts can also lower the pyrolysis activation energy and the degradation temperature of plastics, making more favourable the energy balance of the process. Despite these technical advantages, the economic efficiency of catalytic pyrolysis remains a problem because commercial catalysts are generally expensive and can have a relatively short life in a pyrolysis process, causing the economics of the process to depend on their cost and on a proper regeneration for their reuse. Therefore, developing and producing low-cost catalysts with performances similar to commercial ones could be very interesting for the pyrolysis of plastic wastes [72–74].

Another promising in situ strategy is co-pyrolysis, the simultaneous thermal decomposition of two different types of waste [75]. Usually, the co-pyrolysis with different blending ratios of plastic waste with other feedstocks, such as biomass, vacuum gas oil, oil shales, and heavy crude oils/residues, shows a synergistic effect resulting in improved yields, quality, and composition of the products compared to the pyrolysis of either plastic or biomass alone. The synergistic effect that occurs throughout co-pyrolysis can accelerate the reaction rate, shift the pyrolysis reaction temperature towards low temperature, and improve the selectivity of reaction products.

By closing the loop on plastic waste and recovering valuable resources, pyrolysis contributes to the transition towards a safe circular economy, as it can handle legacy additives and harmful substances and stop the transfer of these substances into new products. Pyrolysis can upgrade the overall quality of the recycling processes, producing secondary feedstock materials that are equivalent to virgin resources and compliant with REACH (EU Regulation, adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals, while enhancing the competitiveness of the EU chemicals industry) [76]. Besides, pyrolysis generates minimal emissions due to the absence of oxygen in the process and avoids GHG emissions that occur in feedstock production and from the incineration of plastic waste [77]. Furthermore, pyrolysis operative conditions prevent dioxin formation in comparison to thermal oxidizing processes [78].

In terms of energy efficiency, pyrolysis can be considered a closed-loop system where the pyrolysis gas produced during the process can be utilized to self-sustain the endothermic reactions in the pyrolysis reactor, thereby enhancing its efficiency and reducing operating costs. In an industrial pyrolysis plant, the required energy has been estimated to be 20–30% of the exploitable energy of the input plastic feedstock [79]. All three main products have a very good heating value and can be efficiently/feasibly stored and utilized flexibly as an energy source [66].

Lastly, the non-oxidizing atmosphere of pyrolysis allows recovery of non-oxidized metals from char, an interesting opportunity in the case of waste with a high content of inorganic fraction, such as laminated and composite plastics or highly contaminated by inorganic foreign materials.

3.3. Present Situation of European Chemical Recycling

Chemical recycling technologies are likely to play a crucial role in the transition towards a circular economy and closed-loop recycling of materials and compounds like hydrocarbons. Today, there are only a few pilot plants in Europe, but many big companies have been investing in research and development in chemical recycling. An ever-increasing number of industrial pilot and demonstration plants for chemical recycling are under construction or are announced. An analysis of these announcements shows that the input

capacity in Europe will more than triple by 2027 [53]. The Plastic Europe association announces that its members are going to invest in Europe more than €8000 M in chemical recycling and to produce 2.8 Mt of recycled plastics by 2030 [80]. Most of these plants will be built in North/West Europe, where Belgium, the Netherlands, France, and Germany account for the largest number of plants. Mixed plastic waste is going to be identified as the main target, and it is important to underline that the most suitable feedstock recycling technologies for the treatment of such complex waste, such as pyrolysis and gasification, represent 80 wt% of the planned capacities. The average capacity of a single plant ranges from 2 to 400 kt/y. Some Italian cases are reported in Figure 6.

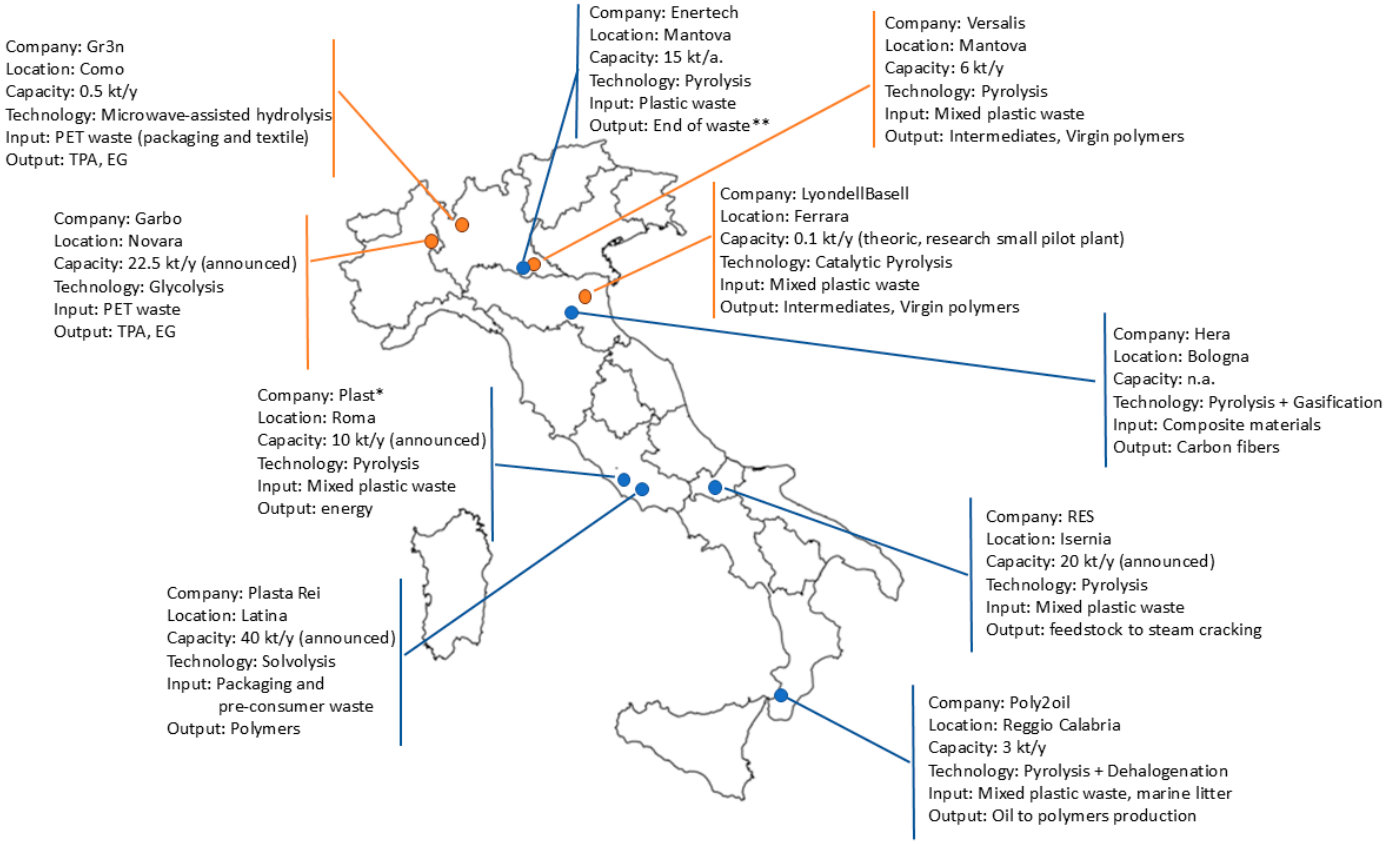


Figure 6. Announced or operative chemical recycling industrial/demonstrative/pilot plants in Italy. Blue points refer to Next Generation EU funding, and orange points refer to other funding. * The pyrolysis plant is auxiliary to the mechanical recycling facility. ** The kind of EoW is not specified.

About pyrolysis, several companies have announced plans in the past few years to build plastic pyrolysis plants in order to convert the oils into a feedstock suitable for the petrochemical industry for the production of monomers and polymers or new chemicals such as aromatics and olefins. Quantafuel owns a plant (20 kt/y) in Denmark, where the liquid product is used by BASF to produce virgin plastics and other feedstocks, and is building a new plant in Sunderland (UK) designed to process more than 100 kt/y [81]. BASF's ChemCycling technology focuses on pyrolysis to turn plastic waste or end-of-life tires into pyrolysis oil. These oils are fed into BASF's Verbund production with the objective to process 250 kt/year of recycled raw materials by 2025 [82]. Plastic Energy currently has two small plants in Spain and has announced a joint venture with Sabic and Total Energies to build advanced recycling plants in France (15 kt/y) and the Netherlands (20 kt/y), respectively [83]. Another plant was announced in France (25 kt/y), and its main output, the synthetic oil, will be used by ExxonMobil's petrochemical complex to create virgin-quality certified circular polymers and other high-value products. The Dutch company

Pryme started in Rotterdam a pyrolysis plant for pre- and post-consumer plastic waste; the start will be carried out gradually through three steps with the aim of reaching a capacity of 30 kt/y oil production [84]. In Italy, Versalis has begun construction of a demo plant to develop its proprietary technology for pyrolysis of mixed plastic waste, not mechanically recyclable. The plant will have 6 kt/y capacity and is scheduled to be up and in service by the end of 2024. The oil will be purified and used in traditional steam-cracking plants to produce intermediates and new virgin polymers [85]. A report published in 2023 by the Italian "Ambrosetti Forum" with the collaboration of industry associations, consortia, and companies foresees a quantity of over 300 kt/y of plastic waste treated through pyrolysis processes in Italy by 2030, with recycling rates between 50 and 65 wt% [86]. Lyondell Basell, in collaboration with the Karlsruhe Institute of Technology (KIT), has developed a catalytic pyrolysis technology for plastic waste, called MoReTec, and built a small-scale pilot facility in Ferrara for research purposes. The goal is to build a 50 kt/y plant in Germany by 2025 [87]. Nextchem announced a demonstration plant with an initial processing capacity of approximately 5 kt/y (with the production of approximately 4.3 kt/y of MMA) for the catalytic depolymerization of PMMA waste [88].

Globally, the number of waste operative gasification plants is estimated to be about 100 facilities, which are primarily dedicated to the production of electricity and heat (<10,000 MW thermal of global waste gasification capacity) [41]. Enerkem with Repsol has planned to build a gasification plant in a petrochemical complex near the port of Tarragona (Spain), able to process 360 kt/y of non-recyclable waste and residual biomass with the production of 290 ML of methanol per year [89]. About the use of SRA, it is widely spreading, and the best-known developers on an industrial scale in Europe are the Austrian company Voestalpine, settled in Linz, which consumes up to 220 kt/y of plastic waste [42]. The Feralpi steel facility was the first Italian company to achieve a complete coal substitution. In other Italian steel facilities (Alfa Acciai, Danieli-Bertoli Safau, and Pittini), the transition is still ongoing at a more gradual pace [33].

Regarding solvolysis technologies, most commercial experiences concern PET chemical recycling. Suez, Loop Industries, and SK Geo Centric will start construction work on a PET recycling plant in early 2025, with plant commissioning expected in 2027 in France. The plant, based on methanolysis to produce monomers DMT and MEG, will treat 70 kt/y of PET waste and will manufacture 100% recycled virgin-quality PET and polyester fibres [90]. Again, in France, Carbios has launched a demonstration plant in 2021 that uses their enzymatic recycling process capable of specifically depolymerizing the PET contained in various plastics or textile waste. The first business unit with a capacity of around 40 kt/y is envisaged by 2025 [91]. Gr3n, a Swiss-based company, has developed a microwave-assisted hydrolysis to recycle packaging and textile PET waste into building blocks and has installed an industrial demonstration plant (about 0.5 kt/y) in the Lombardia region, Italy [92]. Garbo, settled in Northern Italy, has developed a depolymerization process, named ChemPET, which uses glycolysis to produce the monomer BHTE. The technology has been validated at a scale of 10 kg/h, but the fast realization of a 22.5 kt/a plant in Piemonte (Italy) was announced in collaboration with Saipem [93]. About PA, Zimmer and BASF have established in Germany two 20 kt/y PA6 depolymerization recycling production lines, the first based on an acid hydrolysis and the second on an alkali/acid hydrolysis. Furthermore, BASF has another 24 kt/y plant for alkali depolymerization of PA66 [94]. In France, Rhône-Poulenc has established a 50 kt/y PA-66 alkali depolymerization recycling production line [94]. The Italian Aquafil regeneration system with its two recycling facilities in Slovenia depolymerizes PA6 from carpets, fishnets, and waste from nylon industries to produce its following monomer: caprolactam [36,88]. The German company H&S Anlagentechnik developed a glycolysis process applied to PU to produce polyols. A facility

suitable to treat 40,000 mattresses/year has been built in Flevoland in collaboration with the Dutch recycler RetourMatras [35,95]. A similar initiative has been set by Dow Polyurethanes Division in collaboration with Eco Moblier, Orrion Chemicals, and Vita Group under the name of the RENUVA Programme with the aim of realizing a 200,000 mattresses/year capacity facility in France [35].

Dissolution-based approaches do not chemically modify the polymeric plastics' structure; nevertheless, they are recognized as innovative, promising technologies for plastic waste recycling. The German Fraunhofer Institute has developed a dissolution process called CreaSolv that produces plastics with comparable properties to virgin materials, removing contaminants and additives. Polyolefins were the main target of the original process, but other solvents are being studied for the separation of PS, ABS, HIPS, PVC, PET, EVOH, and PA in packaging waste, WEEE, and construction isolation foam [36,41]. A few plants are being built by different companies in the Netherlands and Germany. In 2019, LÖMI opened a site in Germany for the construction of a multi-purpose CreaSolv Demonstration Plant (0.2 kt/y) [96]. Another example is a plant for dissolving PVC in methylethylketone for recycling purposes. It has been in operation in Germany since 2002 with an annual capacity of 10 kt/y [97]. APK developed a solvent-based technology, enabling the separation of the different polymers that compose the multi-layer films and mixed plastic waste. A plant was scaled up in Germany with the capacity of 8 kt/y [36]. Another large-scale APK plant will start construction in 2024 to produce high-quality LDPE recyclates [98].

About HTL, the only case of a commercialized process in Europe is that of the British Mura Technologies, which exploits supercritical water to convert plastic waste into hydrocarbons in the form of naphtha, distillate gas oil, heavy gas oil, and waxy residue. In 2021, Renew-ELP started the construction of a plant in England after obtaining the license from Mura Technology to produce 20 kt/y of circular hydrocarbons. This site is due to be operational by mid-2024 [99]. In September 2022, Mura Technology and Dow announced plans to construct a new facility in Germany. This is the first advanced recycling site to be based at a Dow site and will have a production capacity of 100 kt/y of hydrocarbons [99].

To conclude, Italy shows great potential in the field of chemical recycling technologies thanks to its experiences, infrastructures, waste recycling culture, and knowledge. However, Italy must address the gap with many other European nations that are more advanced in terms of technology implementation and production capacity of chemical recycling plants. France, for instance, stands out with high-capacity solvolysis facilities (up to 70 kt/y) and pioneering enzymatic processes. The UK has invested in very large-scale pyrolysis and HTL plants, while Germany has diversified its chemical recycling industries, also investing in dissolution processes and facilities. In contrast, Italy has concentrated its efforts on the pyrolysis of mixed plastic waste and solvolysis of PET with a maximum capacity of only 40 kt/y (Figure 4).

Many other examples of commercial activities, industrial/demo/pilot facilities, and technology providers around the world can be found in more detailed reports and reviews [35,36,41].

3.4. Solutions, Strategies, and Policies for the Scale-Up of Chemical Recycling Technologies

Probably this is a turning point for chemical recycling in Italy and in Europe, and the fate of these technologies will depend on the success of these new facilities. In any case, several actions need to be taken to ensure investment in the scale-up and for the full deployment of chemical recycling and dissolution technologies.

The European Chemical Industry Council (CEFIC) in its Position Paper of 2022 [100] invites policymakers to accept chemical recycling as an integral solution of a circular

economy for plastic waste, to harmonize definitions for recycling and recyclability, ensuring a level playing field with mechanical recycling, and to extended producer responsibility schemes. Furthermore, Europe should harmonize its waste policy across all member states, implementing and enforcing new and existing legislation to divert plastic waste from landfilling, export, or incineration towards novel recycling routes. Indeed, differences in European members' policies make it more difficult to adopt large-scale chemical recycling technologies, as the lack of uniformity in regulations can create obstacles or uncertainties. The legislative framework relevant for chemical recycling of plastic waste can be considered complex, as it includes policies related to circular economy, waste management, and product safety (especially in the case of food packaging), often going in opposite directions.

However, a mass balance approach, an acknowledged chain of custody that ensures a strictly regulated and verifiable method to calculate the recycled content from chemical recycling in new products, should be implemented and audited by a third party to prevent misconduct and to allow companies to claim and market products as made from recycled materials regardless of their true content [101].

Data need to be generated and collected to improve our understanding of the process and the environmental performance and benefits of chemical recycling. An in-depth knowledge of plastic feedstocks, reaction mechanisms, kinetics, thermodynamics, reactor design, effects of process conditions, and catalyst performance could improve selectivity to produce desired molecules and enable efficient mass and heat transfer. Compared to the high number of life cycle assessment (LCA) studies focusing on other waste technologies, chemical recycling has not yet been given much attention. Chemical recycling technologies seem to be the most environmentally friendly approach for plastic waste that cannot be mechanically recycled [41], but it is necessary to study on a case-by-case basis. Future LCA studies should provide a stronger focus on the material efficiency of these technologies, an appropriate evaluation of their maturity, and surrounding infrastructure and transport logistics, also in comparison to plastics production from virgin fossil feedstock [102]. Furthermore, it is also important to understand that some of the organic molecules produced by chemical recycling technologies, such as aromatic compounds, are dangerous and classified as possible carcinogens. Then, it is strongly recommended to identify all possible risks associated with the implementation of these technologies and to devise the appropriate mitigation strategies [66].

Feedstock heterogeneity is one of the most challenging problems in post-consumer plastic waste treatment. Different compositions of plastic waste input require proper adjustments in the set process parameters and entail the formation of products with different chemical and physical features. Then, access to constant waste in terms of quantity and quality through a long-term agreement between waste suppliers and chemical recycling operators is essential.

In the case of pyrolysis, the hydrocarbon composition of oil is vastly different from that of naphtha or kerosene, and contaminant levels may be so high as to preclude effective use of these products. Often this oil needs to be upgraded or, more simply, diluted with other streams before undergoing subsequent processes, such as distillation or steam cracking. The integration in existing production facilities such as refineries and petrochemical plants could be a simple solution. The pyrolysis oil is rich in hydrocarbons, which makes it an ideal raw material for a refinery. Furthermore, compared to the huge amount of crude oil, the scale is very insignificant at the moment, and the presence of heteroatoms or other compounds is a source of concern in the pyrolysis oil that would disappear [68]. The ReOil pilot plant at the OMV oil refinery simulated the integration of pyrolysis of plastic waste into a conventional refinery in Austria [103]. The proof of concept has been validated, and

the next unit should be capable of processing 2 t/h of used plastic and will thereby help to create a more diverse foundation for crude oil supply.

Commitment from material and chemical producers to use raw materials from secondary sources is a prerequisite for the development of sustainable, feasible, and cost-efficient chemical recycling value chains. The introduction of government economic incentives could reward the use of these secondary sources, at least in the initial phases of the implementation of these technologies. Furthermore, the European Commission is working on integrating recycled content in Green Public Procurement criteria [13]. Similarly, local authorities can support these objectives when purchasing work, goods, or services.

This issue is strongly connected to the presence on the market of well-defined products with clear information about their chemical composition. Often the products derived from these technologies are not standardized, and validated testing methods are almost non-existent [66]. Efforts must be performed to formalize these methods and to set the technical, environmental, and safety requirements that these products must accomplish. The following step is the establishment of EoW criteria, clarifying the point at which EoW status is reached in the chemical recycling processes. Fulfilling the EoW criteria and the REACH regulation, the products of chemical recycling technologies cease to be waste, can be classified as goods (no longer subject to waste legislation), and placed on the market. The same rules for plastic waste and SRM can promote cross-border recycling activities among European countries.

In the design for sustainability or eco-design approach, objects were designed considering their environmental, social, and economic impacts. Among the various principles, eco-design refers to the practice of designing products, processes, and business models in a way that maximizes the reuse and recycling of the component materials. In this case, recycling refers to mechanical recycling, but with the diffusion of chemical recycling technologies, the eco-designed aimed at chemical recycling could gain enormous importance. New research lines could be dedicated to the eco-design of those plastics that their end-of-life management addresses toward chemical recycling technologies [104]. These plastic materials should be designed to favour the production of monomers or depolymerization under milder conditions or avoid the formation of waxes and tars, without compromising their chemical, physical, and mechanical properties related to the function that they must fulfil.

Full deployment and integration of chemical recycling in the European chemical industry also requires big investments into research and development programmes driven by national and European governments. The European Commission has identified research and innovation programs as a relevant measure to implement the plastics strategy. In the last years, about €350 M has been allocated to projects directly related to the plastics strategy (e.g., developing innovative processes, alternative feedstocks, identification of contaminants, and decontamination of plastic waste, etc.) [13]. In the period 2021–2027, the European Commission is continuing to work to further develop plastics-related systemic innovation into business models, products, and materials for the next framework programme, Horizon Europe [105]. In this respect, the Italian government has allocated €265 M (originally €150 M, to which other funds have been added from the surplus of other investment lines) for the construction of new plants or the modernization of old ones for the recycling of plastic waste through the Next Generation EU Plan, Investment 1.2—"Lighthouse" projects for circular economy [106]. The funds are earmarked for private companies to support innovative technologies. Among others, chemical recycling technologies were accepted if the final products were not addressed to energy or fuel production. Overall, 133 project proposals were presented, and a portion of them regarded chemical recycling technologies. In Figure 4, some financed proposals are reported. Other companies

involved with "Lighthouse" projects about pyrolysis of plastic waste are as follows: Itelyum Regeneration, Rigenio (Greenthesis Group), and Centro Diagnostico Baronia.

4. Conclusions

Chemical recycling technologies can play a leading role in delivering on the European targets about plastic waste recycling. In summary, plastic chemical recycling offers several advantages, including recovery of chemicals, monomers, and new polymers with the same characteristics as virgin ones; complementarity with mechanical recycling and energy recovery; versatility; and integrability between different waste treatment technologies and chemical and petrochemical industries. All these features make chemical recycling a real support for the circular economy. So far, these technologies also present important challenges to face, such as energy intensity, emissions, residue management, solvent toxicity, economic viability, and technological hurdles. Addressing these challenges requires a comprehensive approach that encompasses scientific research (studies on reaction mechanisms, kinetics, behaviour of real waste streams, and reactor systems of different scales, etc.), technological innovation, analysis of environmental performances, regulatory frameworks, market dynamics, and stakeholder engagement to unlock the full potential of chemical recycling as a sustainable waste management solution. Furthermore, depending on the polymeric nature and the origin of the waste, some chemical recycling technologies are more suitable than others for the treatment of a certain plastic waste, and then an in-depth knowledge of the waste is a mandatory step before any other consideration.

Despite these problems, for the first time, many facilities for the treatment of plastic waste through different chemical recycling technologies have been announced or are under construction. We are living at a crucial moment for chemical recycling, the fate of which will be determined by the technical and economic success of the plants being built in the world. It is important to highlight that most of these experiences concern the treatment of packaging plastic waste, while facilities for the treatment of plastic waste originating from different product sectors (e.g., ELV, WEEE, building and construction, agriculture, etc.) are very few or lack at all.

Italy is on the right path but behind the situation present in Northern Europe, France, and Spain in terms of both technological diversification and capacity. In the next few years, a survey of the operating installed capacity will have to be carried out in order to compare existing data with the current plant construction planning in Europe.

To conclude, we cannot think and hope that chemical recycling technologies are the solution to plastic waste. They are part of the solution. There is not a single solution with magic. In contrast, the integration with other technologies, the right policies, the separate collection, the eco-design, and consumer education can be the way forward to the victory of this difficult challenge.

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Abbreviations

ABS	acrylonitrile butadiene styrene
ASSORIMAP	(Italian) National Association of Recyclers and Regenerators of Plastic Materials
BAT	best available technology
BDM	Benzenedimethanol
BG	butyl glycol
BPA	bisphenol A
BTEX	benzene, toluene, ethylene, and xylene
BHET	bis(2-hydroxyethyl) terephthalate
BFR	brominated flame retardant
CA	crotonic acid
CEFIC	European Chemical Industry Council
COREPLA	(Italian) National Consortium for the Collection and Recycling of Plastic packages
DMT	dimethyl ester of terephthalic acid
EEE	electric and electronic equipment
EG	ethylene glycol
ELV	end-of-life vehicles
EoL	end of life
EoW	end of waste
EPS	expanded polystyrene
EVOH	ethylene vinyl alcohol
GHG	greenhouse gas
HTL	hydrothermal liquefaction
JRC	Joint Research Centre
HCl	hydrogen chloride
MDA	methylene diphenyl diamine
MEG	mono-ethylene-glycol
MMA	methyl methacrylate
MPO	mixed polyolefins
MRFs	mechanical recovery facilities
PA, PA6, PA66, PA12	polyamide, polyamide 6, polyamide 66, polyamide 12
PBT	polybutylene terephthalate
PHB	poly(3-hydroxybutyrate)
PC	polycarbonate
PC + ABS	polycarbonate/acrylonitrile butadiene styrene blend
PAH	poly aromatic hydrocarbons
PE, LDPE, HDPE	polyethylene, low-density polyethylene, high-density polyethylene
PET	polyethylene terephthalate
PIP	polyisoprene
PLA	poly lactic acid
PMMA	polymethylmethacrylate (acrylic)
PP	polypropylene
PS	polystyrene

PTMT	polytetramethylene terephthalate
PU	polyurethane
PUs	polyurethanes
PVC	polyvinyl chloride
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SRA	secondary reduce agent
SRM	secondary raw materials
TAM	terephthalamide
TDA	2,4- and 2,6-toluenediamine
TPA	terephthalic acid
XPS	expanded extruded polystyrene
WEEE	waste electrical and electronic equipment

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