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Chemical recycling: comprehensive overview of methods and technologies

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ABSTRACT

Plastic pollution has emerged as a global environmental crisis, prompting the search for innovative solutions to manage and repurpose plastic waste sustainably. Chemical recycling has garnered attention as a promising strategy to address this challenge by converting discarded plastics into valuable feedstocks and products. Drawing upon statistical data and a thorough review of the literature, this paper examines the diverse methodologies and technologies employed in chemical recycling, highlighting key advancements and their potential environmental and economic impacts. The aim of this article is to provide a comprehensive overview of various methods of chemical recycling of plastics. In this article, the reader is offered a detailed overview of various chemical processing methods, including hydrolysis, glycolysis, enzymatic degradation, acid hydrolysis, supercritical fluid depolymerisation, catalytic pyrolysis, fast pyrolysis, microwave pyrolysis, fluidised bed pyrolysis, plasma gasification, steam gasification, oxidative degradation, hydrothermal liquefaction, biological depolymerisation, and electrochemical processing. The literature cited in the article allows the reader to gain an in-depth understanding of processes at Technology Readiness Levels (TRL) 4 to TRL 9, depending on the chosen technology.

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Plastic pollution; waste management; chemical recycling; sustainability

1. Introduction

In the face of a mounting plastic pollution crisis, the world is contending with millions of tons of plastic waste inundating landfills and oceans annually (Europe 2016). The widespread proliferation of plastic materials over the past century has engendered a profound environmental crisis, characterised by the pervasive accumulation of plastic waste in terrestrial and marine ecosystems worldwide (Lockie 2023). As plastic production continues to soar, outpacing corresponding advancements in waste management infrastructure, the urgency for sustainable solutions to the plastic pollution crisis has never been more pronounced (Z. Chen et al. 2023). The genesis of the plastic waste crisis can be traced back to the mid-20th century, coinciding with the advent of mass production and consumption of synthetic polymers (Zalasiewicz, Gabbott, and Waters 2019). Plastics rapidly permeated various sectors, displacing traditional materials due to their affordability, versatility, and durability (Rodrigues et al. 2019). Once referred to as 'materials of 1,000 uses', plastics meet demands in everything from clothing and automotive sectors to the manufacturing of medical equipment and electronics. However, the exponential growth of plastic production has outpaced corresponding advancements in waste management infrastructure, exacerbating the proliferation of plastic waste and its attendant environmental impacts. According to the latest statistical data, over 450 million tons of plastic are currently produced worldwide, indicating that global plastic production has doubled in just the last two decades (Department 2024; Hannah Ritchie). Plastics production in Europe totalled 58.7 million metric tons in 2022, a decrease of nearly two million metric tons from the previous year (Department 2024). PP (polypropylene) is the polymer with the greatest share of production in Europe at 19.2 percent, followed by PE at 17.2 percent (Jaganmohan 2024). Half of all plastic waste is made up of packaging plastic (Ncube et al. 2021). Half of the plastic collected for recycling is exported to be treated in countries outside the EU. Reasons for export include the lack of capacity, technology or financial resources to treat the waste locally (Plastic waste and recycling in the EU: facts and figures, 2024). In the past, a substantial portion of plastic waste exported from the EU went to China. However, with China imposing stricter regulations on plastic waste imports, it's probable that EU exports will decline further. This situation raises the concern of heightened incineration and landfilling of plastic waste within Europe. Turkey was the main destination for European Union exports of plastic waste in 2021, with a volume of 395,000 metric tons. Malaysia ranked second that year, receiving over 133,000 metric tons of plastic waste from EU member states (Main destinations for plastic waste exports from the European Union (EU-27) in 2021, by country [Online], 2023). For the EU, Plastics Europe estimates that out of the 30 million tonnes of plastic waste produced annually, 35 % is effectively sent to recycling with the rest being sent to incineration with energy recovery (42 %) or to landfilling (23 %). In addition to this, the European Commission has decided to ban the export of waste to countries outside the European Union by reviewing the Waste Shipment Regulation. It is further prohibited to transport plastic waste to countries such as Malaysia, Thailand, and Indonesia (Ban on shipping plastic waste outside the EU, 2023). Moreover, the export of plastic waste to developing countries exacerbates environmental injustices and underscores the interconnectedness of global waste management systems (Z. Liu, Adams, and Walker 2018).

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Today, there are many different types of plastic and its compounds in the world, each of which has its own unique properties (Yani et al. 2020). The most common classification system for plastics is the Resin Identification Code (RIC) (Agarwal, Gudi, and Saxena 2022). The most well-known are polyethylene (PE), which can be manufactured at different densities depending on the desired characteristics of the product, polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC) (Cantor and Watts 2011). Plastics converters demand in the European Union (EU-27 + 3) totalled 50.3 million metric tons in 2021. Of this total, PP accounted for 10 million metric tons. The second most in-demand polymer in the EU-27 that year was low-density polyethylene (LDPE) and linear LDPE (Jaganmohan 2024). The durability and persistence of plastics facilitate their widespread dispersal, with fragments accumulating in remote environments, from polar ice caps to deep-sea trenches (W. C. Li, Tse, and Fok 2016). Furthermore, the ingestion of plastic debris by marine organisms and terrestrial wildlife not only engenders physical harm but also facilitates the bioaccumulation of toxic pollutants, thereby amplifying ecological disruptions and endangering human health (Gall and Thompson 2015). The escalating magnitude of plastic pollution underscores the urgency of implementing sustainable solutions to mitigate its environmental impacts and promote the transition towards a circular and regenerative plastics economy (Sigler 2014). EU waste policy aims at establishing a circular economy where materials and resources are maintained in the economy for as long as possible and where the disposal of waste is the last option of waste management (Waste management indicators, 2022). There are currently three main methods of waste processing: chemical, mechanical, and energy recovery. The difference between these methods lies in the fact that chemical recycling involves breaking down the chemical structure of plastic polymers into their constituent monomers, while mechanical recycling focuses on the physical processing of plastic without altering its chemical structure. As for the latter, energy recovery occurs through the incineration of plastic waste. The maximum amount of plastic waste that can be sorted and mechanically processed is estimated at 29–45% (L. Shen and Worrell 2024). Traditional recycling methods fall short, often resulting in downcycling or incineration rather than effective recycling (Perugini, Mastellone, and Arena 2005). This dilemma exacerbates the emission of greenhouse gases, contributing to climate change. Compounding the issue, recycling streams are frequently contaminated, compromising the quality of recycled materials (Schyns and Shaver 2021). The effectiveness of mechanical recycling depends on factors like the quality of the collected plastic and the sorting techniques used. It's most effective for certain types of plastic, like PET, HDPE, and PP (Vollmer et al. 2020). Mechanical recycling, while valuable, faces limitations in effectively handling certain technical challenges associated with plastic waste (Ragaert, Delva, and Van Geem 2017). The process is hindered by the inability to manage mixed or contaminated plastics (Angyal, Miskolczi, and Bartha 2007). Recycled plastic obtained through mechanical recycling isn't as high in quality as virgin plastic. It might have impurities, reduced strength, and colour variations (Vilaplana and Karlsson 2008). Furthermore, the mechanical recycling of certain polymers can lead to a degradation of their properties, rendering them less suitable for high-value applications (Ravve 2013). Mechanical processing handles a separated single-polymer stream, which is washed, granulated, and then re-extruded to obtain recycled pellets ready for use (Al-Salem, Lettieri, and Baeyens 2009). These limitations make it challenging to achieve a closed-loop system for all types of plastic waste (Garforth et al. 2004). The inadequacy of existing waste management practices underscores the imperative for innovative approaches to plastic recycling, such as chemical recycling, which offer the potential to unlock value from plastic waste and promote circularity in the plastics value chain. In this dynamic landscape, chemical recycling emerges as a pivotal player in the quest for a more sustainable and efficient approach to handling the global plastic waste crisis (Quicker, Seitz, and Vogel 2022). Chemical recycling, as a concept, has been under development for several decades, but its increased attention and adoption are more recent. Chemical recycling processes, based on depolymerisation and processing of the raw material, break down long hydrocarbon chains in the plastic into shorter hydrocarbon fractions or monomers through chemical, thermal, or catalytic processes. By means of chemical processing, plastic waste can be transformed into a full-fledged market product that can be used, for example, in the fuel industry, serving as an alternative to commonly used agricultural products (bio-components) (Garside 0000).

The global plastic pollution crisis is characterised by the rapid growth of plastic production, which exceeds the capacity of waste management infrastructure, as well as the accumulation of millions of tons of plastic waste in landfills and oceans. The shortcomings of traditional disposal methods, particularly mechanical recycling, often result in waste being incinerated or landfilled, exacerbating environmental issues and contributing to greenhouse gas emissions. The export of plastic waste from the EU, driven by the lack of local processing capacity, has been complicated by the introduction of restrictions on plastic imports in countries such. Chemical recycling is considered a promising alternative approach, involving the breakdown of polymers into monomers and the conversion of waste into useful products, though it faces technical and economic challenges. The need to implement sustainable solutions is a key factor in reducing the negative impact of plastic on the environment and creating a circular economy in plastic recycling.

This article provides a detailed description of modern chemical recycling methods. It also presents a comprehensive literature review that fully describes the state of chemical recycling technologies. In addition, the challenges faced by plastic chemical recycling as a whole are discussed. The value of this article lies in its relevance. The world is currently on the brink between the depletion of Earth's resources along with global pollution of the planet and that pivotal moment when a viable and effective technology for recycling plastic waste will be found. This work describes the most well-known technologies for chemical recycling of plastic, along with an analysis of their environmental and economic impacts. The study reviews about 200 sources of scientific literature, providing a detailed understanding of the current state of the technology. This sufficient level of information opens up new opportunities for finding solutions to reduce harmful impacts on the planet without economic losses. The detailed analysis and data-driven approach make the article an important resource for decision-makers, industry professionals, and researchers.

2. Chemical recycling technologies

Chemical recycling involves the transformation of plastic polymers into smaller molecules or monomers through various chemical processes. These processes aim to break down the long chains of polymers found in plastic waste, allowing for the recovery of valuable resources that can be used to produce new materials or fuels (Prajapati et al. 2021). Today, there already exists a considerable number of chemical recycling methods. Classifying chemical recycling technologies involves categorising them based on various criteria such as the type of chemical reactions involved, feedstock materials, process conditions, and environmental impact (Solis and Silveira 2020). In this work, we classified known techniques by the type of chemical reaction. The classification results are presented in Figure 1.

In this study, plastic chemical recycling technologies are classified according to the type of chemical reaction occurring in the process. During depolymerisation, polymer chains are broken down into monomers or smaller molecules through chemical reactions (Miao, von Jouanne, and Yokochi 2021). As for pyrolysis, molecular breakdown occurs based on a thermal process and in the absence of oxygen (Anuar Sharuddin et al. 2016). During gasification, polymer decomposition occurs through high-temperature reactions with controlled amounts of oxygen or steam (Lopez et al. 2018). In the oxidation process, plastic decomposition occurs using various types of oxidants (Pifer and Sen 1998). In other cases, plastic conversion occurs either through water, solvents, microorganisms, or electrochemical reactions.

2.1. Hydrolysis

Hydrolysis of plastics typically involves the breaking of ester bonds present in the polymer chains, leading to the formation of the corresponding monomers. Hydrolysis is a heterogeneous reaction that occurs on the surface of the material (Lusty Beech et al. 2022). The most typical product for hydrolysis is PET. The process of this technology is influenced by numerous factors. The resulting outcome depends on the catalyst used, temperature, pressure, and the size of the plastic particles (Y. Li et al. 2022). The operating temperature for this technology ranges from 150°C to 300°C (Damayanti, Wu, and 2021). Characteristic of this process is the use of catalysts such as sulphuric acid, hydrochloric acid, metal oxides (for example, TiO2, ZnO, MgO), and zeolites (for example, ZSM-5) (Campanelli, Cooper, and Kamal 1994). The environment of hydrolysis is also important, which can be acidic, alkaline, or neutral (Kandasamy et al. 2020). Neutral hydrolysis is considered the most environmentally friendly because it does not require the use of aggressive chemicals, as the reaction occurs at a pH close to neutral (Siddiqui et al. 2021). Neutral hydrolysis can be conducted at lower temperatures compared to acidic or alkaline hydrolysis, which often require higher temperatures to facilitate the reaction, leading to greater energy efficiency (S. Mancini and Zanin 2004). However, neutral hydrolysis does not account for mechanical impurities in PET waste, resulting in the final product containing more impurities than the product obtained through alkaline hydrolysis (Abedsoltan 2023). The main products of hydrolysis are terephthalic acid, ethylene glycol, and diethylene glycol (Sabde, Yadav, and Narayan 2023). A more comprehensive overview of the output products obtained from chemical recycling can be seen in Table 1.

2.2. Glycolysis

Glycolysis involves the depolymerisation of plastics, typically PET, through a series of chemical reactions (Krehula et al. 2009). In glycolysis, PET polymer degraded in molecular level in the presence of trans-esterification catalyst. Most frequently used glycols for this purpose are ethylene glycol, diethylene glycol, propylene glycol, and dipropylene glycol by involving: catalytic, solvent-assisted, supercritical, and microwave-assisted glycolysis (Sheel et al. 2019). The ester bonds in

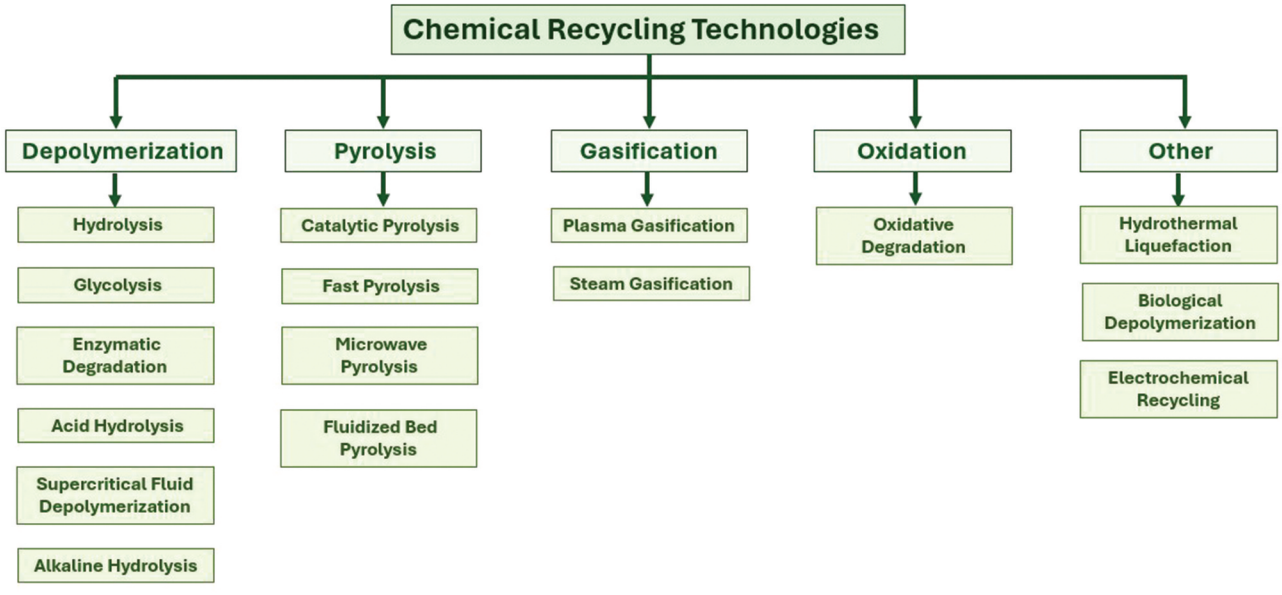

Figure 1. Classification of plastic chemical recycling technologies according to the type of chemical reaction.

Table 1. Output products of plastic chemical recycling processes.

Recycling method	Solid (s)	Liquid (l)	Gaseous (g)	Uses	Source
Hydrolysis	Pet flakes (terephthalic acid residues, solid impurities)	Terephthalic acid, ethylene and diethylene glycol	N/a (sometimes carbon dioxide, methane)	S – recovered and reused in the production of new pet. L – used as a raw material for synthesising new polymers, as antifreeze, etc. G – used as a fuel source.	Kumagai et al. (2018), Bi et al. (2021)
Glycolysis	Residual solid impurities (polyurethanes), unreacted pet fragments	Bhet (bis (2-hydroxyethyl) terephthalate) monomer and excess glycol	N/a	S – fillers or reinforcing agents for use in new pu products. L – used in the synthesis of new pet materials.	Shirazimoghaddam et al. (2023), Shukla and Harad (2005)
Enzymatic degradation	Oligomeric polymer fragments	Terephthalic acid, ethylene glycol and organic acids	Can include carbon dioxide and, in some cases, methane and h2o,	Monomers and oligomers can be repolymerised or utilised in the synthesis of new materials, alcohols and organic acids can serve as precursors in chemical industries, and gaseous by-products contribute to the carbon cycle, either naturally sequestered or released into the atmosphere.	Tamoor et al. (2021)
Acid hydrolysis	Carbon-rich char	Terephthalic acid, smaller oligomers also oils or waxes	Include hydrogen, methane, carbon dioxide, and other light hydrocarbons	S – used in applications such as fillers in construction materials or as a precursor for activated carbon production. L – reused in the production of new plastic materials. Oils or waxes refined into synthetic lubricants or used as fuel. G – used as energy sources.	Vaishnavi, Gopinath, and Ghodke (2022), Moghbeli, Namayandeh, and Hashemabadi (2010)
Supercritical fluid depolymerisation	Unreacted pet, solid carbon residues (char)	Oil (naphtha-like hydrocarbons)	Hydrogen, methane, and carbon dioxide, ethylene, propylene	S – filler material in construction. L – used as gasoline blendstocks, feedstocks for chemical production, or for direct fuel use. G – used as energy sources.	Miao, von Jouanne, and Yokochi (2021), Preetam et al. (2023)
Alkaline hydrolysis	Unreacted polymer	Ethylene glycol, terephthalic acid, caprolactam	Ammonia, carbon dioxide	S – recovered and reused in the production of new pet. L – used as a raw material for synthesising new polymers, as antifreeze, etc. G – used as a fuel source.	Kandasamy et al. (2020), W. An et al. (2023)
Catalytic pyrolysis	Char	Liquid hydrocarbons (C_5-C_{20} range alkanes, alkenes)	Methane, ethylene, hydrogen	S – used in energy production or as a precursor for activated carbon L – used as drop-in fuels for diesel engines or further refined into high-value chemicals G – used for energy and synthesis.	Yek et al. (2024,) Djandja et al. (2022), Akhtar et al. (2024), J. Liu et al. (2024)
Fast pyrolysis	Char (solid carbon, primarily carbon black)	Pyrolysis oil (mixed alkanes, alkenes, aromatic hydrocarbons)	Syngas (H_2, CO, CO_2, CH_4)	S – can be further processed into activated carbon L – refined into fuel G – used for power generation or chemical synthesis.	Wong et al. (2023), Natesakhawat et al. (2024)
Microwave pyrolysis	Char (carbon black, silica residues if present)	Oil (C_5-C_{12} hydrocarbons), wax (paraffin-like hydrocarbons)	Syngas	S – as construction materials or as a precursor for carbon nanotubes. L – can be used directly as fuel or further refined into higher-value chemicals. G – used for energy production.	C. Yang et al. (2023) X. Shen et al. (2022), Y. Cui, Y. Zhang, Y. Cui, et al. (2023)
Fluidised bed pyrolysis	Biochar (carbonaceous material, potential trace metals)	Pyrolysis oil (C_5-C_{20} hydrocarbons, tar)	Syngas	S – used for soil amendment or fuel L – used as chemical feedstocks or for refining into fuels like diesel G – used for energy or chemical feedstock.	Hafeez et al. (2023) Y. Cui, Zhang, Cui, et al. (2023)
Plasma gasification	Vitrified slag (silicates, aluminosilicates, metal oxides)	N/a	Syngas (h_2, CO, CO_2, CH_4)	S – used for construction materials L – G – used for power generation or chemical production	Xiao et al. (2022) Bhatt et al. (2024), Mallick and Vairakannu (2023)
Steam gasification	Residual char (carbon-rich solid)	N/a	Syngas	S – used as a material for activated carbon production, soil amendment (biochar), or even as a solid fuel in some cases. L – G – used for chemical synthesis, power generation, or as industrial fuel.	Pravin, Ahmed Al, and Srinivasakannan (2012) H. Xu and Shi (2022), Parparita et al. (2015)
Oxidative degradation	Partially oxidised polymer fragments and carbon-rich materials	Carboxylic acids (e.g. acetic acid), lactones, alcohols, ketones, and aldehydes.	Carbon dioxide, carbon monoxide, ammonia, and hydrogen cyanide (hcn)	S – filler material in construction. L – have potential applications as feedstocks in the chemical industry G – used as a fuel source.	Yao et al. (2022) Ma et al. (2024), S. Xu et al. (2024)
Hydrothermal liquefaction	Biochar (carbon, mineral residues)	Crude bio-oil (fatty acids, phenols, hydrocarbons)	CO_2, light hydrocarbons (C_1-C_4)	S – used for soil improvement L – used for fuel production G – used for energy recovery.	Boel et al. (2024) Y. Liu et al. (2022)

(*Continued*)

Table 1. (Continued).

Recycling method	Solid (s)	Liquid (l)	Gaseous (g)	Uses	Source
Biological depolymerisation	Biomass residues (organic material, unreacted polymers)	Terephthalic acid, ethylene glycol	Carbon dioxide, methane	S – used as soil conditioners or compost, contributing to soil fertility L – can be further processed into biofuels or used in the production of biochemicals, such as solvents or precursors for biodegradable polymers G – used as a source of renewable energy.	Ghosh, Pal, and Ray (2013,) Mohan et al. (2024), Y. Zhang et al. (2024)
Electrochemical recycling	Carbon-rich materials	Include a range of hydrocarbons, alcohols, acids, and esters	Hydrogen, methane, carbon monoxide, and carbon dioxide, oxygen from electrolysis	S – activated carbon production or as fillers in construction materials L – can be refined into fuels such as diesel or gasoline G – can be used in various industrial processes or as a clean fuel.	Catizane, Jiang, and Sumner (2024), W. Zhang, Killian, and Thevenon (2024)

PET are cleaved, leading to the formation of EG and TPA or its derivatives as reaction products (Aguado et al. 2014). The success of glycolysis relies heavily on the optimisation of operating conditions, including temperature, pressure, reaction time, and the ratio of reactants (Shojaei, Abtahi, and Najafi 2020). Typically, glycolysis is carried out at elevated temperatures ranging from 150°C to 250°C, under atmospheric or slightly elevated pressure (Karayannidis and Achilias 2007). The catalyst is one of the most important factors in the PET glycolysis process (Xin et al. 2021). Catalysts such as zinc acetate, antimony trioxide, titanium dioxide, zinc oxide, and zeolites are commonly used (Yue et al. 2011). The development of efficient catalysts and process optimisation strategies is essential to enhance the economic viability and scalability of glycolysis technologies (X. Zhang et al. 2018). The reaction time can vary from several hours to days, depending on the specific process design and desired outcomes (Lei et al. 2022,). The monomers obtained from glycolysis can be utilised as building blocks for the synthesis of new polymers or speciality chemicals, thereby closing the loop of plastic material cycles (Nikles and Farahat 2005).

2.3. Enzymatic degradation

This method utilises specific enzymes to break down the polymeric structure of plastics into smaller, more manageable molecules that can be further processed into useful products (Banerjee, Chatterjee, and Madras 2014). The success of enzymatic degradation relies heavily on the selection of appropriate enzymes (Mohanan et al. 2020). Enzymes catalyse the cleavage of ester linkages, resulting in the fragmentation of polymer chains into smaller oligomeric fragments (Aguiar et al. 2024). Enzymes such as lipases, proteases, and esterases have shown promising activity in degrading various types of plastics, including PET, PE, and PP (Kaushal, Khatri, and Arya 2021). Optimisation of reaction conditions is imperative to maximise the efficiency of enzymatic degradation while ensuring the preservation of enzyme activity (Roohi et al. 2017). Key parameters, including temperature, pH, substrate concentration, and enzyme concentration, are meticulously regulated to facilitate optimal enzymatic activity and substrate accessibility (Papadopoulou, Hecht, and Buller 2019). The temperature range for enzymatic degradation typically spans from 20°C to 60°C, depending on the specific enzymes employed, while the pH optimum varies according to the enzyme's characteristics, encompassing acidic to alkaline conditions (Giraldo-Narcizo et al. 2023). Monomeric units recovered from enzymatic degradation serve as precursors for the synthesis of new polymers, biofuels, or chemical feedstocks through polymerisation reactions (Thiyagarajan et al. 2022). Dimers and oligomers derived from enzymatic degradation find applications as chemical intermediates or additives in various industrial processes (Tournier et al. 2023,). It is also worth noting that this method shows promise in addressing the problem of textile waste accumulation, particularly in the enzymatic degradation of natural fibres in polyester-cotton fabrics to recover polyester (Navone et al. 2020). In this process, specific enzymes, such as cellulases, are used for enzymatic degradation, which can break down natural fibres like cotton (composed of cellulose), leaving the polyester

intact (Egan et al. 2023). However, its industrial implementation requires further research and optimisation.

2.4. Acid hydrolysis

Acid hydrolysis of plastic, particularly polymeric materials like PET or PS, involves breaking down the long polymer chains into smaller molecules through the action of strong acids in the presence of water (Islam et al. 2023). Strong acids, such as sulphuric acid or hydrochloric acid, protonate the oxygen atoms in these bonds, leading to the formation of hydroxyl groups (S. D. Mancini and Zanin 2007). Subsequent hydrolysis of these modified bonds by water results in the scission of polymer chains, yielding smaller molecules. The kinetics of acid hydrolysis are influenced by factors such as temperature, acid concentration, and reaction time, which dictate the rate and extent of polymer degradation. Usually, the process temperature ranges from 100°C to 150°C. Typically, concentrated acids are used. The acid concentration is crucial and varies depending on the type of plastic and the desired reaction rate (Yoshioka, Sato, and Okuwaki 1994). The output products typically include smaller molecules such as monomers, oligomers, and fragments of the polymer backbone (Alias and Abdul-Hakim 2022).

2.5. Supercritical fluid depolymerization

Supercritical fluid depolymerisation is an innovative chemical process used to break down plastics into their constituent monomers or other valuable chemical products using supercritical fluids as a medium (J. Xu et al. 2021). Common supercritical fluids used in SCFD include carbon dioxide and water (Goto 2010). In SCFD, the supercritical fluid serves as both a solvent and a reactant (Sako et al. 1997). The supercritical fluid penetrates the polymer matrix, swelling it and reducing its viscosity. This allows the fluid to interact with the polymer chains, leading to cleavage of the polymer backbone and the formation of smaller molecules, such as monomers or oligomers (Goto, Sasaki, and Hirose 2006). SCFD is typically conducted at temperatures above the critical temperature of the supercritical fluid, ranging from 100°C to 400°C (Y. Li and Wang 2020). The pressure is maintained above the critical pressure of the supercritical fluid, typically ranging from 70 to 300 bar (Y. Liu et al. 2024). Catalysts may be used to enhance the rate and selectivity of the depolymerisation reaction. Common catalysts include metal oxides, zeolites, and acid/base catalysts (Sepini et al. 2024).

2.6. Alkaline hydrolysis

Alkaline hydrolysis is similar to the processes of hydrolysis described above, differing only in that in this case, the degradation of polymeric materials occurs with the aid of alkalis. In the case of acid hydrolysis, acids act as catalysts that enhance the protonation of the polymer's functional groups, whereas in alkaline hydrolysis, alkalis act as nucleophiles that attack specific atoms in the polymer, such as the carbonyl carbon atom, leading to bond cleavage and the formation of new products. In this process, crushed plastic is mixed with an alkaline solution, and after the reaction is complete, the mixture is cooled, and the resulting products are separated by filtration (Z. Guo et al. 2024). Alkaline hydrolysis of plastic materials, particularly PET, mainly yields two important products: ethylene glycol and terephthalic acid (Barredo et al. 2023). The efficiency of this process depends on the concentration of the alkaline solution and the solvent system used (Maniar, Kalonia, and Simonelli 1992). For example, studies have shown that in the presence of a polar aprotic solvent and a small amount of water, the degradation of unsaturated polyester resin into valuable raw materials, such as products containing carboxylate, is significantly enhanced due to the solvent's role in fragmenting the polymer network (Brueckner et al. 2008; Thorn, Thorne, and Cox 2004,). Similarly, optimising reaction conditions, such as temperature and solvent composition, can lead to high yields of TPA and EG, with some studies achieving up to 95% conversion under mild conditions. The main parameters affecting the process are temperature, which typically ranges from 150°C to 200°C, pressure from 2 to 3 MPa, and reaction duration from 1 to 6 hours (Bhogle and Pandit 2018,; Z. Guo et al. 2024; Karayannidis, Chatziavgoustis, and Achilias 2002; Kumagai et al. 2018; Tsintzou and Achilias 2013,). Of course, the setting of all these parameters depends on the alkali used. Typical alkalis for the process are sodium hydroxide, potassium hydroxide, and ammonium hydroxide (Čorak et al. 2022). The choice of a specific alkali for alkaline hydrolysis depends on the desired process characteristics and final products, considering the specifics of the materials and technical requirements (Z. Guo et al. 2023).

2.7. Catalytic pyrolysis

Catalytic pyrolysis involves the thermal decomposition of plastic materials in the presence of a catalyst. Catalytic pyrolysis depends on factors such as temperature, retention time, composition of the feedstock, and catalyst (Miandad et al. 2016). There is an evident strong influence of reaction temperature and residence time on the output products of pyrolysis. The temperature typical for the pyrolysis process ranges from 400°C to 600°C (Velghe et al. 2011). The retention time typically depends on various factors, including reactor design, operating conditions, and the specific catalyst used (Scheirs and Kaminsky 2006). Typically, the retention time varies in the range of 20 minutes to 60 minutes (D. Chen et al. 2014; Deka and Misra 2024). Product output depends on the feedstock used, characterisation of which can predict the product distribution to a certain extent (Goswami 2004). Compared with single plastic pyrolysis, pyrolysis of mixed plastics yields less than 50 wt% oil product, which may be equivalent in terms of quality (Grause et al. 2011). Among the applied catalysts can be FCC, HZSM-5, Zeolite-ß, Fe2O3, natural zeolite, Red Mud (Achilias et al. 2007; K.-H. Lee 2012; López et al. 2011; Ojha and Vinu 2015). The produced liquid fuel has the potential to be used in several energy-related applications such as electricity generation,

transportation fuel, and heating purposes, its average HHV (higher heating value) is 40 MJ/kg (Rehan et al. 2016).

2.8. Fast pyrolysis

Fast Pyrolysis of plastic typically occurs at temperatures between 500°C to 800°C, with variations depending on the type of plastic and the specifics of the process technology used (Maqsood et al. 2021). Fast pyrolysis involves rapid thermal decomposition of plastic materials in the absence of oxygen. This type of pyrolysis typically occurs at higher temperatures and relatively short retention times (from seconds to minutes) (Singh et al. 2019). In this case, the rate of plastic heating is important, with an average value of 50°C min^{-1} (Hall and Williams 2006). The primary products of fast pyrolysis include pyrolysis oil, which can be further processed into transportation fuel, solid residue or char, a gas mixture including hydrogen, methane, carbon monoxide, and carbon dioxide, which can be used for heat and power generation or as chemical feedstock (Williams 2006). Much depends on the composition of the feedstock and the quality of the products obtained, as in other cases. Due to the high temperatures required to carry out the process, this technology is quite energy-intensive. Among the benefits of this method of chemical recycling, one can mention its relatively high efficiency. As for the drawbacks, it includes high energy demand (Jamradloedluk and Lertsatitthanakorn 2014).

2.9. Microwave pyrolysis

Microwave radiation is used to generate heat in plastic material by interacting electromagnetic waves with polar molecules present in the plastic (Aishwarya and Sindhu 2016). Microwave radiation uniformly heats the substance as a whole instead of initially heating the outer surface, as with conventional heating (Arshad et al. 2017). In this case, the critical parameter is the level of microwave radiation power, which determines the rate of heating and temperature distribution inside the plastic material (X. Hu et al. 2023). Higher power levels result in faster heating, but they can also lead to localised overheating and thermal degradation (Undri et al. 2014). The main output products are gas, oil, wax, and oil+wax (Goodman 2014). The characteristic temperature for this process ranges from 400°C to 1200°C. Precise control of the pyrolysis temperature is necessary to optimise the yield and quality of the product (Ludlow-Palafox and Chase 2001). For microwave pyrolysis, on average, 1 ton of plastic requires 1389 kWh of energy (C. Yang et al. 2023). Also characteristic of this process are additives such as silicon carbide or activated charcoal, which are used in proportions ranging from 5% to 20% relative to the feedstock. These additives enhance microwave absorption, providing more efficient and uniform heating (Jing et al. 2021). One of the drawbacks of this method is its strong dependence on the dielectric properties of the material (Putra et al. 2022).

2.10. Fluidised bed pyrolysis

Solid particles (typically sand, alumina, or silica) are fluidised by a gas stream (usually nitrogen or steam) flowing upward through the reactor. The high surface area and intimate contact between the solid particles and the plastic feedstock promote rapid and efficient heating, leading to faster pyrolysis rates (Kaminsky 2021). In this method, plastic materials undergo thermal decomposition in the absence of oxygen at elevated temperatures (typically from 400°C to 800°C) inside a reactor with a pseudo-liquid layer (Kaminsky 1995). The size of solid particles matters; smaller and denser particles provide better fluidisation and heat transfer, while larger particles may lead to poor mixing and heat distribution (Gaston et al. 2011). The residence time of the gas in the reactor, also known as the gas residence time, influences the extent of pyrolysis reactions and product yields. It is controlled by adjusting parameters such as gas flow rate, reactor geometry, and particle size distribution (Mastral et al. 2002). Although specific wattage is variable, typical small to medium-scale operations might consume around 50 kW to 500 kW, depending on scale and throughput. Energy consumed by the process was affected by temperature and feed mass flux. On the other hand, as energy consumption depends on the amount of feed reacting, higher feed fluxes distributed heat among a higher amount of mass, decreasing the energy consumed per kilogram of gasoline produced (De la Flor-Barriga and Rodríguez-Zúñiga 2022). The consumption is minor and mainly related to cooling and condensation systems. The main output products are pyrolysis oil, non-condensable gases, and biochar (Zhang et al. 2014,). Among the prospects of this method, flexibility and scalability can be highlighted. This process can be adapted to different operational scales and conditions required for obtaining products of desired quality (Clemente-Castro et al. 2023).

2.11. Plasma gasification

Plasma gasification is an allothermic gasification process where the heat necessary for endothermic reactions is provided by thermal plasma, typically generated by direct current arc plasma torches (Arena 2012). As the waste comes in contact with the thermal plasma, its organic fraction is converted into syngas and its inorganic fraction is transformed into vitrified slag (Willis, Osada, and Willerton 2010). This process occurs at extremely high temperatures, typically ranging from 3000°C to 8000°C (Fabry et al. 2013). At the output, synthetic gas and slag are obtained (Kwon and Im 2024). Energy consumption can range from 800 to 950 kWh per ton of processed waste (Cudjoe and Wang 2022). Depending on the waste input and desired quality of syngas, additives like lime or carbon sources may be used to adjust the chemical reactions and slag properties (Cho et al. 2015). The advantages of this method lie in its ability to work with practically any type of waste. However, the disadvantages are that this technology requires significant energy consumption and substantial initial investments.

2.12. Steam gasification

Steam gasification of plastic involves using steam to decompose plastic waste at high temperatures, typically between 600°C to 1200°C, in a controlled oxygen environment (Lee, Chung, and Ingley 2014). Outputs include syngas, composed of about 20% hydrogen and 20% carbon monoxide, with the rest being CO_2 and other gases. Syngas is used in chemical synthesis, power generation, and as industrial fuel (Wilk and Hofbauer 2013). The carbon conversion efficiency can reach up to 91%, with carbon dioxide emissions as low as 15% volumetrically under optimal conditions (Burra and Gupta 2018). To improve the quality of the output products, catalysts such as potassium, lithium, or nickel are added (Abu El-Rub, Bramer, and Brem 2004). Compared to pyrolysis, gasification can handle a more diverse range of feedstocks and operates at higher efficiencies, potentially over 80% for thermal conversion.

2.13. Oxidative degradation

Oxidative degradation of plastics refers to the chemical breakdown of plastic materials through reactions with oxygen (Beachell and Nemphos 1956). This process breaks down large polymer chains into simpler compounds. Although it does not always result in the formation of the original monomers, it is still a chemical transformation of plastic. This process can be accelerated by adding substances like ferric stearate, a common photo-oxidation aid. The degradation starts with the cleavage of carbon-hydrogen and carbon-carbon bonds in the polymer chains, leading to the formation of various reactive radicals such as primary alkyl macroradicals and hydrogen radicals. These radicals, upon reacting with oxygen, mark the transition of the material into an oxidative degradation phase, which produces numerous oxygen-containing functional groups and reduces the molecular weight of the polymer (Wang et al. 2023). Oxidative degradation of plastics typically occurs at temperatures ranging from 30°C to 150°C (Rasselet et al. 2014). The efficiency of the process is influenced by the type of plastic, temperature, residence time, and catalysts (Rovaletti et al. 2023). As catalysts, TiO_2 and ZnO can be considered, which contribute to the degradation of plastic polymers under the influence of light (Li et al. 2023). Generally, this process results in smaller molecules such as monomers, oligomers, and polymers with reduced molecular weight, as well as various types of oxygen-containing groups like carboxylic acids, aldehydes, and alcohols. In more complex oxidation processes, particularly those involving photocatalysis, the end products, in addition to the aforementioned compounds, may include water, carbon dioxide, and mineral acids (Wang et al. 2023).

2.14. Hydrothermal liquefaction

Hydrothermal liquefaction is a process that emerged for the valorisation of biomass, and it can also be applied to plastic waste to provide energy recovery and obtain chemical products (Seshasayee and Savage 2020). Hydrothermal Liquefaction typically operates at temperatures ranging from 250°C to 374°C. Optimal conversion rates are often achieved between 300°C and 350°C, maintaining high pressure between 10 and 25 MPa (Mathanker et al. 2021). The output products of this process are crude bio-oil, biochar, and gases (Helmer Pedersen and Conti 2017). Due to the requirement for high temperatures, the process is quite energy-intensive (Jatoi et al. 2022). A disadvantage of this method is that controlling by-products, especially from the aqueous phase, typically requires additional processing stages (Rahman et al. 2023). The efficiency of hydrothermal liquefaction of plastic is influenced by temperature, pressure, the ratio of water to plastic, residence time, and of course, various types of catalysts (Lu, Jan, and Chen 2022; Y. Shen 2020).

2.15. Biological depolymerization

Biological depolymerisation of plastics is a process that primarily utilises enzymes to break down plastics into their monomeric forms under mild conditions (Gluth et al. 2022; Gu 1999). This method is particularly effective for plastics like PET (Hussein, Alzuhairi, and Aljanabi 2018). Enzymes such as PETase and its variants can catalyse the hydrolysis of PET, effectively cleaving ester bonds and converting the plastic back into its original monomers, such as ethylene glycol and terephthalic acid (Wu et al. 2024). Biological depolymerisation typically occurs at moderate temperatures, 28–50°C (Meenakshisundaram et al. 2022). The main additives include specific enzymes and sometimes mild chemicals for pretreatment to enhance the substrate's susceptibility to enzymatic action (Shah et al. 2008). The typical output products are monomers such as ethylene glycol and terephthalic acid from PET (Chen and Patel 2012). The main advantages include lower energy requirements, while a disadvantage is the lower depolymerisation rate and potential inefficiency in breaking down more resistant polymers without thorough pretreatment (Koshti, Mehta, and Samarth 2018). It is also worth noting that biological depolymerisation is a related method to enzymatic degradation. Both methods involve the use of biological systems to facilitate the breakdown of materials (Mohanan et al. 2020). One could say that these two methods complement each other: enzymes can accelerate decomposition, while biological systems provide the environment and additional mechanisms for the breakdown process (Guo et al. 2024). From a technical perspective, the difference between biological depolymerisation and enzymatic degradation lies in the mechanisms and conditions under which they occur. Specifically, enzymatic degradation involves the use of specific enzymes that break down polymers into monomers or oligomers by catalysing certain chemical reactions. In contrast, biological depolymerisation encompasses chemical or microbiological actions, including enzymatic degradation (Aristizábal-Lanza et al. 2022; Weng, Peng, and Han 2021). Enzymatic degradation is a more specific and controlled process compared to biological depolymerisation, but the latter has a broader range of conditions under which it can occur. Neglecting either of these methods would be unwise, as each is critical for the effective recycling of polymers under different conditions, providing a comprehensive approach.

2.16. Electrochemical recycling

At the core of this process are electrochemical reactions through which polymers are broken down into smaller molecules or even monomers. This process begins with the purification and shredding of plastic, which is then placed in an electrochemical chamber containing an appropriate solvent and electrolyte. Voltage is then applied, and the plastic undergoes oxidation or reduction reactions on the electrodes (Catizane, Jiang, and Sumner 2024). The efficiency of this process depends on the material and design of the electrode, the type of electrolyte, voltage and current parameters, temperature, pressure, and of course, the pretreatment of plastic waste (Petersen et al. 2021). Characteristic of this process are temperatures ranging from 350°C to 500°C (Jiang et al. 2020). The output of electrochemical recycling of plastics includes valuable chemicals such as terephthalate and formate, derived from PET (Shi et al. 2021).

Also, for a comprehensive understanding of the suitability of the studied technologies for different types of plastics, refer to Table 2.

3. Environmental and economic implications

The aim of full-scale implementation of chemical recycling is to address the issue of plastic waste accumulation while obtaining valuable materials. One of the most advertised advantages of chemical processing is its potential to reduce dependence on fossil fuels. However, the environmental benefits of chemical processing are not without significant caveats (Chilton, Burnley, and Nesaratnam 2010). The question of assessing the life cycle of the chemical recycling process remains open in this situation. The benefits derived from chemical plastic processing are evident, but currently, there is insufficient comprehensive research to fully assess the impact of these technologies on the environment and the human body (Xayachak et al. 2023). Considering that chemical recycling technologies are not widely implemented in practice, existing models and their calculations have significant differences (Zou et al. 2023). LCA processes for chemical recycling are a developing area (Davidson, Furlong, and McManus 2021). The problem lies in the diversity of LCA methods and the need for researchers to establish project-specific parameters, meaning that the results of one LCA are rarely comparable with others (Alhazmi, Almansour, and Aldhafeeri 2021). Although mechanical recycling has a better environmental profile than chemical recycling, chemically recycled fibres can be used in a wider range of applications compared to mechanically recycled fibres (Shen, Worrell, and Patel 2010). An analysis of the life cycle of three scenarios of plastic waste processing (mechanical processing, enhanced mechanical processing, and processing of raw materials by pyrolysis) showed that quality-oriented processing is better both environmentally and financially (Faraca, Martinez-Sanchez, and Astrup 2019). Today, it is worthwhile to focus on researching methods of chemical plastic processing, rather than continuing to compare them with mechanical methods (Gandhi et al. 2021). To conduct LCA, it is necessary to have a comprehensive dataset to ensure reliable research results (Fonseca et al. 2023). The most researched and applied methods are plastic pyrolysis and gasification (Solis and Silveira 2020). Researchers (Aryan et al. 2021) conducting a comparative environmental assessment of hydrolysis, alcoholysis using methanol, alcoholysis using ethanol, and direct combustion of PLA waste within the system boundaries from waste collection and transportation to the replacement of conventional products with recyclates, concluded that all three chemical recycling technologies perform better from an environmental perspective compared to direct combustion. Energy consumption and emissions are critical factors in assessing the impact of chemical processing methods on the environment. It has been studied that the main impact of chemical recycling is associated with the electrical energy required to achieve the necessary temperature for the required reactions that occur in the reactor, while processed heat and natural gas are secondary sources of energy (Xayachak et al. 2023). The LCA study (Jeswani et al. 2021) suggests that chemical plastic processing (via pyrolysis) has approximately a 50% lower impact on climate change and energy use over the life cycle compared to energy recovery from mixed plastic waste, but it exerts a greater impact in other categories (acidification and eutrophication). Chemical processing often requires a significant amount of heat and electrical energy. The environmental benefits largely depend on the source of energy. When energy from fossil fuels is used, the overall carbon emissions may outweigh the environmental benefit of reducing plastic waste. Among the methods studied above, plasma gasification is considered the most energy-intensive. The reason is the use of a plasma torch to create a high-temperature plasma arc, which gasifies the raw material in the presence of steam. This process is highly energy-intensive, with consumption ranging from 11.0–30.3 MJ/kg due to the need to generate plasma at temperatures exceeding 3000°C (Rutberg et al. 2011, 2013; Surov et al. 2017). The main energy consumption in gasification is intended for heating reactors to high temperatures. High temperatures promote the production of cleaner syngas with fewer pollutants (Woolcock and Brown 2013). Regarding steam gasification, this method is no less energy-intensive, as it also requires high temperatures (600°C – 1200°C). However, in this case, the main portion of energy is consumed for heating water to produce steam – approximately 12–20 MJ/kg (Afzal et al. 2023; Kantarelis et al. 2009; Shan, Pandyaswargo, and Onoda 2023). The pyrolysis technology, which is based on thermal decomposition processes (500–800°C), requires a significant amount of energy on its own to achieve the necessary temperatures (Luo et al. 2021; Motasemi and Afzal 2013; Qureshi et al. 2020). On average, the pyrolysis of plastic requires 4–10 MJ/kg of energy (Faisal et al. 2023; Zhou et al. 2021). Depolymerisation processes (Figure 1), although requiring lower temperatures (180–374°C), are still quite energy-intensive, as some of them necessitate maintaining pressures around 22.1 MPa (Han et al. 2019; Khalil 2019; Rubio Arias and Thielemans 2021). On average, the energy consumption of depolymerisation processes ranges from 2.8 to 9 MJ/kg (W. Liu et al. 2021; Pereira et al. 2024). Oxidative degradation requires significantly lower temperatures compared to the processes described above and is less energy-intensive (2–7 MJ/kg). However, on the other hand, this process is highly

Table 2. A comprehensive presentation of the investigated plastic recycling technologies.

Technologies	Plastic type	Benefits	Disadvantages	Company	Looking ahead to the future	Recent research
Hydrolysis	PET, PLA, nylons, PC	High purity output, chemical recycling	Energy-intensive	Ioniqa Technologies, Eastman Chemical Company	Optimisation of temperature and catalysts for energy savings	Huang et al. (2024) Taxeidis et al. (2024), Bayer et al. (0000) Abdikamalova et al. (2024), Y. Hu, Lin, and Craig (2024)
Glycolysis	PET, PBT, PLA, PC	Recovering monomers, lower energy than hydrolysis	Catalyst recovery issues	Loop Industries, Indorama Ventures	Development of advanced catalyst systems for efficiency	Kurneshova et al. (2024) Olazabal et al. (2024), Luna et al. (2024) Amundarain et al. (2024),
Enzymatic Degradation	PLA, PET, PBT	Environmentally friendly, low temperatures	Slow reaction rates, scalability	Carbios, Novozymes	Engineering enzymes for faster, more versatile plastic breakdown	Akram et al. (2024) Y. An et al. (2024), Aguiar et al. (2024)
Acid Hydrolysis	PET, PLA, nylons, PC	Handles contaminated plastics	Corrosive, hazardous waste	BASF, DuPont	Improved acid recovery systems for safer processing	Rana et al. (2023) Mehmood et al. (2023), Abedsoltan (2023)
Supercritical Fluid Depolymerization	PET, PU, PS, PC, PLA	High reaction rates, solvent recovery	High energy input	Repsol, ExxonMobil	Optimising energy usage through alternative heating technologies	Mathew et al. (2024), Z. Shen et al. (2024), Demirkaya, Cocero, and Cantero (2024)
Alkaline Hydrolysis	PET, nylons, PUR, PLA	High monomer yields, simple chemistry	Corrosive, requires neutralization	Gr3n Recycling, Coca-Cola Company	Developing safer, more scalable alkaline systems	Cao et al. (2022), Z. Guo et al. (2024),
Catalytic Pyrolysis	PE, PP, PET, PS	Converts plastic to fuel, lower energy requirement	Catalyst deactivation, emissions	Agilyx, Pyrowave	Development of long-lasting catalysts for continuous processing	Gonzalez-Aguilar, Pérez-García, and Riesco-Ávila (2023), Mishra et al. (2023), Abbas-Abadi et al. (2023)
Fast Pyrolysis	PE, PP, PET, PS, PVC, MPW (Mixed Plastic Waste)	Rapid conversion of plastic waste into usable oil	Complex mixture of products	BASF, Brightmark	Improved systems for better control over product composition	Dewi et al. (2024), Ren et al. (2024), Supriyanto, Richards, and Richards (2024)
Microwave Pyrolysis	PE, PP, PS, PVC, PET, PA, ABS, MPW	Efficient heating, rapid reactions	High capital cost, scale-up challenges	Pyrowave, GreenMantra Technologies	Improved scalability of microwave reactors	Putra et al. (2024), X. Wang et al. (2024), Bandi, Sulttan, and Rohani (2024)
Fluidised Bed Pyrolysis	PE, PP, PS, PET, PVC, MPW	High heat transfer, large processing capacity	Complex operation, difficult optimisation	Recycling Technologies Group, BASF	Enhancing reactor designs for large-scale operations	K. Chen et al. (2024), Choi et al. (2024), Genuino et al. (2024), Żukowski et al. (2024),
Plasma Gasification	PET, PE, PP, PS, PVC, MPW	Can process a wide variety of plastic types	High energy consumption, expensive infrastructure	Alter NRG, Hitachi Zosen Inova	Reducing energy demand and infrastructure costs	Yousef et al. (2024) (Kwon and Im 2024), Chu et al. (2024), Fathi et al. (2024),
Steam Gasification	PP, PE, PS, PET, PVC, MPW	Produces high-quality syngas from mixed plastic waste	High capital and operational costs	Anellotech, Linde	Exploring syngas applications for industry use	Parrillo et al. (2024), G.-B. Chen and Chang (2024), González-Arias et al. (2024)
Oxidative Degradation	PE, PP, PS, PVC, PET	Reduces plastic size for further processing	Limited byproduct value, loss of material	BP, Shell, ExxonMobil	Combined approaches with other recycling technologies	Ceretti et al. (2023), Gijsman and Fiorio (2023), Amato et al. (2024)
Hydrothermal Liquefaction	PE, PP, PS, PVC, PET	Converts plastic into liquid fuels	High temperature and pressure required	Resynergi, Waste2Energy	Research on lower energy requirements for hydrothermal processes	Tito et al. (2024), dos Passos et al. (2024), Boel et al. (2024)
Biological Depolymerization	PET, PA, PU, PLA, Nylon	Sustainable, low-energy processes, biodegradable enzymes	Long reaction times, scalability	Carbios, Novozymes, LanzaTech	Genetic modification of enzymes for mixed plastic degradation	Stoddard et al. (2024), Affes et al. (2024), Amalia et al. (2024)
Electrochemical Recycling	PET, PE, PP, PS	No external heating, low energy consumption potential	Requires development of efficient electrode materials	IBM Research, University of Manchester	Development of new electrode materials for enhanced efficiency	Rani et al. (2024) Hughes et al. (2024), Catizane, Jiang, and Sumner (2024)

dependent on auxiliary factors, such as catalysts (Chamas et al. 2020; Singh and Sharma 2008). For the depolymerisation of plastic via the hydrothermal liquefaction method, it is necessary to create supercritical water conditions (>374°C; > 23 MPa). These requirements make the procedure quite energy-intensive, consuming approximately 12 to 22 MJ/kg (Laredo, Reza, and Meneses Ruiz 2023). For the biological degradation process, the majority of energy consumption is attributed to the cultivation of microbes, enzyme production, and the operation of the bioreactor itself (energy for mixing, temperature control, and system monitoring), ranging between 1–3 MJ/kg (Ellis et al. 2021; Mat Yasin, Akkermans, and Van Impe 2022). The energy consumption during the process of electrochemical recycling of plastic directly depends on the design of the electrochemical cell (electrode materials, membrane, electrolyte composition), as well as the voltage and current requirements. This consumption typically ranges between 5–12 MJ/kg (Liu et al. 2022; Petersen et al. 2021; Zhang, Killian, and Thevenon 2024). From an energy perspective, the prospects for chemical recycling are ambiguous. On the one hand, there is potential for significantly reducing the volume of plastic waste and creating a more circular economy. On the other hand, the current high energy demands make it less attractive. Until there is a sufficient amount of available energy from renewable sources, the aforementioned processes will balance between reducing environmental impact by decreasing plastic waste and emissions associated with energy. Additionally, some chemical processing methods generate hazardous by-products or require the use of harmful chemicals, posing risks to both the environment and human health if not properly managed. For chemical recycling methods such as glycolysis, catalytic pyrolysis, fluidised bed pyrolysis, hydrothermal liquefaction, and electrochemical processing, the use of various types of catalysts is inherent to increase reaction efficiency, reduce energy requirements, and improve the quality of end products (Huang et al. 2022; Inayat et al. 2022; Khoonkari et al. 2015; H. Wang et al. 2009). However, the use of catalysts also introduces additional considerations regarding the production, regeneration, and disposal of catalytic materials (Lerici, Renzini, and Pierella 2015). Additionally, handling catalysts requires extra actions that often create additional emissions into the environment (Agarski et al. 2017; Argyle and Bartholomew 2015; Trimm 2001; Van Allsburg et al. 2022,). In the case of electrochemical recycling of plastic, the environmental load increases due to the handling of electrode materials and waste. Moreover, additional emissions are generated when using enzymatic degradation technology, particularly as a result of the industrial production and purification of enzymes, and the maintenance of optimal conditions for enzyme activity (Saravanan et al. 2021). In the case of acid hydrolysis, additional emissions originate from the production and handling of strong acids, the energy required for the reaction, and the treatment of acidic waste. Biological depolymerisation generates additional emissions from the cultivation, maintenance, and potential genetic modification of microorganisms, as well as the disposal of biological waste (Chapman, Ismail, and Dinu 2018). Researchers from (Uekert et al. 2023,) have shown that mechanical processing outperformed enzymatic hydrolysis, glycolysis, and methanolysis of PET flakes, as well as the production of virgin plastic in terms of economic and environmental considerations. However, it demonstrated lower material quality and other technical indicators. Meanwhile, among the methods of PET chemical recycling, glycolysis provided the best economic and environmental performance. Similar results were shown in the study (Cosate de Andrade et al. 2016), where the LCA (life cycle assessment) analysis of PLA (polylactic acid) utilisation indicated that mechanical processing has the least environmental impact, followed by chemical recycling and composting. The study (Meys et al. 2020) shows that all chemical recycling pathways can reduce the impact of global warming and the depletion of fossil resources if sorted plastic packaging, which would otherwise be processed at municipal waste-to-energy plants, is used.

To gain a comprehensive understanding of the overall impact of the processes under study, it is advisable to conduct research using LCA, which offers a holistic approach to determining environmental impacts. LCA is recognised as the best tool for assessing the life cycle impact of products or processes (2006; Finnveden et al. 2009). The LCA allows for the identification of the most energy-intensive and resource-demanding stages that have the greatest environmental impact, particularly during the sorting, cleaning, and processing of polymers. By analysing these stages, it is possible to identify 'hotspots' where significant optimisation can occur, such as through the implementation of advanced sorting technologies that reduce contamination and material loss. LCA also enables the evaluation of the energy efficiency of different recycling methods, such as mechanical or chemical recycling, helping to choose optimal strategies based on specific plastic types. The advantage of using LCA for waste management system analysis lies in its ability to provide a comprehensive view of the processes and impacts involved, even considering their connections with other sectors (Finnveden et al. 2007). One of the key benefits of this method is its ability to provide useful information at the design stage, as it allows for the identification of planning alternatives (Scipioni et al. 2009). From an economic perspective, LCA helps reduce costs by optimising processes and improving the quality of secondary raw materials, potentially increasing the profitability of plastic recycling. One of the key solutions is the adoption of 'eco-design' concepts, which focus on developing materials that are easier to recycle, thus reducing processing costs and increasing the value of the final product. Unfortunately, existing LCA studies on chemical recycling methods for plastics have gaps in the research on relevant waste types and the methods themselves (Astrup et al. 2015; Laurent et al. 2014). The most extensively analysed chemical recycling methods using LCA are pyrolysis and gasification (Ardolino et al. 2018; Demetrious and Crossin 2019; Gracida-Alvarez et al. 2023; Xayachak et al. 2023). According to an LCA study (Stančin, Strezov, and Mikulčić 2023) the environmental impact of pyrolysis can be reduced by using energy from renewable sources. Research (Pires Costa, Vaz de Miranda, and Pinto 2022), suggests that pyrolysis experiments should focus on improving carbon conversion efficiency and utilising renewable energy sources in conjunction with chemical recycling approaches, as the significant emissions during this process are primarily related to energy consumption

(Azam, Vete, and Afzal 2022; Das, Liang, and Dunn 2022; Stančin, Strezov, and Mikulčić 2023). Despite this, plastic pyrolysis technology is still insufficiently researched, and to fully transition from a comparative perspective to a more holistic approach – where plastic pyrolysis is considered an integral part of a sustainable waste management system – there is a need for a specialised LCI database (Xayachak et al. 2022). Life cycle assessment of the gasification process (Dong 2016) demonstrates clear advantages of gasification over conventional incineration technology. The LCA of plastic gasification revealed that the primary challenge is the electricity required to decompose plastic waste in the reactor (Xayachak et al. 2023). On the other hand, the authors of (Afzal et al. 2023) in their study of the life cycle of methanol and hydrogen produced through gasification of municipal plastic waste, found that greenhouse gas emissions from MPW gasification pathways are estimated to increase by 166% and 36%, respectively. However, LCA results (Lan and Yao 2022,) show that hydrogen derived from mixed plastic waste has a lower environmental impact compared to single-stream plastic. Additionally, when comparing the life cycle of gasification and landfilling of municipal solid waste, the authors (Ouedraogo, Frazier, and Kumar 2021) emphasise that gasification has a significantly lower impact on human health, including the risks of cancer and non-cancer diseases. Regarding LCA studies of hydrolysis and glycolysis processes, most researchers agree that the availability and quality of data are low (Davidson, Furlong, and McManus 2021). The authors of (Ügdüler et al. 2020) in their LCA study of the PET hydrolysis process, concluded that the key to reducing carbon emissions lies in maintaining low energy consumption by increasing the solid-to-liquid ratio and avoiding excessive water addition during monomer purification. As for the LCA results of two PET glycolysis processes, it was found that glycolysis using ethylene glycol has a higher global warming potential than glycolysis using propylene glycol (Iturrondobeitia, Alonso, and Lizundia 2023). There are significantly fewer available LCA studies for processes such as biological depolymerisation and enzymatic degradation. For instance, the authors of (Tonini and Astrup 2012) when comparing the life cycle of enzymatic plastic recycling with incineration, concluded that enzymatic recycling could represent a valuable alternative to incineration from both an energy and environmental perspective, particularly if the subsequent options for utilising the solid and liquid fractions include co-combustion and anaerobic digestion for biogas production. Another LCA study indicates that in the depolymerisation process, the degree of PET breakdown, solid loading, enzyme cost, and enzyme loading are key cost factors (A. Singh et al. 2021). It is also worth noting that research on biodegradable plastics plays a significant role in the development of biological depolymerisation and enzymatic degradation (Amobonye et al. 2021; Mohapatra et al. 2024; Rezvani Ghomi et al. 2021; Y. Yang et al. 2024). In the case of electrochemical plastic recycling, fewer LCA studies are available, with existing research only partially addressing this topic (Iannicelli-Zubiani et al. 2017; Zuiderveen et al. 2021). Given that electrochemical recycling of metallised plastic has demonstrated significant environmental improvements through the electrochemical process (Walls et al. 2023), LCA studies of this technology have potential for future implementation (Rubin et al. 2014). Life cycle assessments of supercritical fluid depolymerisation technology have been published in several studies, which generally indicate a greater environmental impact compared to incineration and landfilling processes (when recycled products are not considered) (Pillain et al. 2019). Energy demand could be reduced through energy optimisation, achieved by utilising waste heat generated during the chemical breakdown of plastic waste (S. Lee et al. 2024). Hydrothermal liquefaction of plastic has not been extensively studied in LCA terms, with the most detailed descriptions found in (Hussin et al. 2023) and (U. Lee, Benavides, and Wang 2020). As for oxidative degradation, no comprehensive LCA studies are available, only partial considerations on the topic (Croxatto Vega, Gross, and Birkved 2021; García-Depraect et al. 2021; Oh and Stache 2024). From the above, it can be concluded that most chemical recycling processes for plastics require further research from a life cycle assessment perspective. LCA studies of chemical recycling processes should include a set of factors and assumptions based on social, economic, and technological forecasts (Davidson, Furlong, and McManus 2021).

A plausible scenario for the development of plastic recycling involves combining several methods that complement each other and ultimately yield the most effective result. This is demonstrated in the study (Khoo 2019) which shows that the life cycle assessment (LCA) analysis of the scenario 'Recycling rate of 10.64% sent to MR (Mechanical Recycling) plus potential 2 × P (Pyrolysis); the rest of it sent to WTE (Waste-to-Energy)' has the least environmental impact.

Establishing a balance between environmental and economic considerations is crucial for achieving the widespread adoption of this revolutionary technology. The economic viability and scalability pose challenges for the widespread implementation of chemical recycling. Currently, these processes require higher financial investments compared to traditional recycling methods, making them less economically attractive. This economic challenge affects the scalability of chemical substance recycling and, consequently, the potential environmental benefits. The results of study (Baldwin et al. 2023) are an example of significant economic challenges in plastic recycling through pyrolysis and gasification, with the latter path being particularly complex. The study (Roux and Varrone 2021) shows that the concept of bioplastic recycling can play a crucial role in transitioning to a more biologically-based and circular plastic sector. The high cost of catalysts, which directly affects the efficiency of the recycling process and the quality of the end products, also plays an important role in this situation (Payne and Jones 2021). Significant initial investments required for the large-scale application of chemical recycling can be a serious challenge for investors. However, the study (Voss, Lee, and Fröhling 2022) indicates that, under certain aspects, such an approach can significantly enhance economic competitiveness. The price competitiveness of chemically processed plastic is influenced by global market prices for virgin plastic, derived from petroleum products. Fluctuations in oil prices can affect the economic viability of chemical plastic recycling, as lower oil prices may make virgin plastic cheaper, thereby reducing demand for recycled materials. Market

dynamics results show that consuming natural gas in the waste HDPE chemical recycling process increases the natural gas' market price and supply by 0.1%, while onsite manufacturing propylene decreases propylene market price by 5.46%, decreases propylene supply by 8.8%, and increases the propylene demand by 10.2% (Zhao and You 2021). Study (Hernández et al. 2023) indicates that lubricant oils obtained through pyrolysis and hydrogenolysis have positive return on investment, while gasification, hydrocracking, and HTL (Hydrothermal Liquefaction) have costs higher than profit. Thus, it is evident that there is currently no perfect chemical recycling process for plastic that can be seamlessly applied in practice. The methods described above indicate that the problematic areas are either significant energy consumption, high costs, or increased environmental emissions.

4. Market trends

The demand for recycled plastic is increasing due to consumer awareness and heightened regulatory pressure on manufacturers to use environmentally friendly materials. Government policy plays a crucial role in the economic viability of chemical processing. Subsidies, tax incentives, and grants can offset some of the initial costs and make the activity more profitable. The views of modern scientists and environmentalists on chemical processing vary. Advocates, such as authors (Calinescu et al. 2024), argue that advancements in catalyst and reactor design can significantly improve the efficiency of chemical processing, making them more robust and economically viable. By improving the efficiency and selectivity of catalysts, it is possible to maximise the yield of desired products while minimising by-products and waste (Nawaz, Odriozola, and Yu 2024). Others believe that recycling alone is not the solution; the only way forward is to completely rethink the way we produce, transport, consume, and dispose of products; this means we need a full redesign and an immediate focus on reusable products and closed-loop systems (Greenpeace 2023; Mitchell 2019). The latter argue that existing problems can be addressed by reducing plastic production and usage, improving mechanical recycling methods, and promoting alternative materials. To date, there are many organisations that attempt to apply or research various methods of chemical recycling of plastic waste on a larger scale. One of the most well-known organisations in Europe is Plastic Energy, founded in 2011 in London. It recycles plastic using its own patented process, where plastic is heated in the absence of oxygen to form hydrocarbon vapour, which is then condensed into recycled oil called TACOIL™ (Thermal Anaerobic Conversion Oil). According to the LCA conducted by the organisation for this technology, the type of energy used is significant, and switching to 100% renewable electricity can significantly reduce the carbon footprint of the chemical recycling process. The BASF ChemCycling organisation is also engaged in chemical recycling of plastic. The LCA conducted by Sphera for BASF, reviewed by three independent experts, concluded that the pyrolysis of mixed plastic waste emits 50% less CO_2 than incineration. The study also showed that CO_2 emissions decrease when producing products based on pyrolysis oil using the mass balance approach instead of petroleum. Another organisation, Mura Technology, recycles plastic using its own developed Hydrothermal Processing technology, called HydroPRS™. This process involves recycling plastic using supercritical water (water under high pressure and temperature). The LCA study of the process shows an 80% reduction in GWP (Global Warming Potential) compared to energy from waste (incineration), saving over 1.8 tons of CO_2 eq. GWP per ton of processed plastic. The organisation Quantafuel offers a solution where plastic waste is heated, broken down, and reassembled into valuable products. The main advantage of their technology is that it allows impurities and a mix of different colours and types of plastic. The process is based on pyrolysis, followed by the purification of pyrolysis gas and the use of a two-stage catalyst in the gas phase. The gas is then condensed and separated into the necessary oil fractions through distillation. Founded in 2003, Clariter has developed and refined its own chemical recycling technology. Clariter uses a three-stage chemical recycling process, which includes thermal cracking, hydrorefining, and distillation and blending. This process can handle most types of plastic from all waste streams, requiring relatively simple preparation of the raw material. In the future, Clariter aims to expand its operations worldwide by establishing full-scale recycling plants in various regions. Covestro is a well-known organisation focusing on innovation and sustainable development, investing in research and development to expand chemical recycling capabilities. The organisation actively employs pyrolysis, hydrolysis, and glycolysis in its practices. Loop is another organisation engaged in sustainable plastic chemical recycling technologies. Loop's depolymerisation technology breaks down previously unrecyclable polyethylene terephthalate plastic and polyester fibre waste into their base building blocks, dimethyl terephthalate and monoethylene glycol, using low heat and no added pressure. Another notable organisation striving to implement large-scale chemical recycling is ORLEN Unipetrol in the Czech Republic. ORLEN Unipetrol is a significant player focusing on several advanced recycling methods, including catalytic pyrolysis and hydrothermal liquefaction. Their pyrolysis plant in Litvínov converts mixed plastic waste into hydrocarbons for the production of new polymers and fuels. The organisation Pryme also works on optimising the pyrolysis process. Various associations also play an important role in promoting the implementation of chemical recycling and supporting recycled products. Plastics Europe is one such organisation that works to popularise the benefits of plastics while advocating for environmental practices and supporting the transition to a circular economy. Plastics Europe collaborates with policymakers, industry stakeholders, and research institutions to promote regulations and policies that support the development and implementation of chemical recycling technologies. Plastics Europe supports the development and implementation of various chemical recycling technologies, such as pyrolysis, gasification, or depolymerisation. Despite the extensive research into different methods of chemical recycling of plastic, it is still difficult to say whether the benefits we gain justify the side disadvantages resulting from the

application of these technologies. To date, there is insufficient convincing research aimed at life cycle assessment to definitively say that large-scale chemical recycling of plastic is warranted.

5. Discussion

According to the presented results, chemical recycling of plastics shows great potential for addressing the issue of plastic waste surplus. The article provides a comprehensive overview of existing methods, such as hydrolysis, glycolysis, pyrolysis, and others. Each of these methods has its own advantages and disadvantages, highlighting the need for an individualised approach when selecting a technology depending on the type of plastic waste and the desired recycling outcomes.

5.1. Possible solutions to overcome challenges

Chemical methods of plastic recycling, while holding significant potential in addressing plastic pollution, face a number of substantial challenges that can be overcome through comprehensive measures at the research, policy, and infrastructure levels. To reduce energy consumption and the cost of chemical recycling, it is essential to invest in research and development of new, more energy-efficient technologies. One of the key areas is investment in research aimed at improving catalysts and processes, which will reduce energy consumption and increase the efficiency of recycling complex polymer waste. For instance, research into the development of low – temperature depolymerisation processes could significantly lower energy costs, which is one of the main factors contributing to the high cost of chemical recycling. At the same time, political initiatives, such as tax incentives and subsidies, can stimulate innovation in this field, while strict waste management regulations will increase the demand for chemically recycled products. An example is the European Union, which, as part of its 'Circular Economy Action Plan', proposes measures to increase the recycling rates of plastics and the use of secondary materials. The efficient recycling of mixed and contaminated plastics is one of the major technical challenges, so particular attention should be paid to optimising feedstock composition and establishing plastic manufacturing standards that facilitate easier subsequent recycling. Furthermore, cooperation between government institutions, industry, and research organisations – such as partnerships involving large chemical companies – can accelerate the market introduction of new technologies. To reduce production costs, it is advisable to scale up chemical recycling, which will allow for economies of scale, as well as to integrate these processes with existing industrial infrastructures. For example, integrating chemical recycling with petrochemical plants can lower initial capital investments. Another important strategy is increasing consumer awareness and expanding producer responsibility, which entails holding manufacturers accountable for managing plastic waste after the end of its lifecycle. From an environmental impact perspective, the focus should be on developing energy-efficient technologies and implementing carbon capture and utilisation technologies to minimise climate change impacts. The secondary products market also requires support, as chemically recycled products must compete in quality and price with virgin materials, making the development of technologies that can produce high-quality secondary polymers critically important. Therefore, a comprehensive approach that includes technological innovation, regulatory support, infrastructure development, and reducing environmental impact is key to overcoming the main challenges of chemical plastic recycling.

5.2. Assumptions and limitations of this study

In conducting this research, several assumptions and limitations were applied that affect its results and interpretation. It was assumed that current chemical recycling technologies for plastics, such as pyrolysis, gasification, and hydrolysis, will remain stable in the coming years, based on their evolutionary development and current scientific publications (Solis and Silveira 2020). However, future advancements in the development of new catalysts or process improvements may alter their efficiency and economic viability. The energy consumption estimates, based on average data, vary depending on conditions, but in general, pyrolysis and hydrolysis require significant energy resources – up to 7,000 MJ per ton of feedstock (D. Chen et al. 2014), which may fluctuate depending on regional conditions. Environmental assessments of CO_2 emissions are based on current sources, which indicate the potential for a 50% reduction in emissions through pyrolysis compared to incineration. However, actual figures depend on the energy source used in the process and may change with the adoption of renewable energy resources. A significant limitation is the reliance on secondary data sources, which may lead to variations in results due to differences in research methodologies and regional characteristics. Additionally, the diversity of approaches to LCA affects the ability to compare results across different studies. Moreover, the economic assessment of technologies depends on current energy and raw material prices, which can fluctuate, creating additional risks for the large-scale industrial adoption of these methods. Technologies such as plasma gasification or microwave pyrolysis may require substantial initial investments and have high energy demands, complicating their scalability. At the same time, while some technologies demonstrate high potential in laboratory conditions, their practical implementation requires significant time and resources, casting doubt on the economic viability of chemical recycling technologies at the current stage of development.

6. Conclusion

As the world seeks sustainable solutions to the plastic waste crisis, chemical recycling stands out as a promising avenue with the potential to reshape the future of waste management. Each of the methods described in the article has its advantages and disadvantages. Among the main drawbacks are significant indirect emissions associated with the production and consumption of the energy required for most processes. Solving this problem requires a sufficient amount of energy from renewable sources, which is currently difficult to achieve with large-scale implementation of chemical recycling. Another issue is the additional emissions generated during the chemical

recycling process. These include substances such as catalysts, enzymes, and acids, depending on the chosen chemical recycling technology. These substances are typically used to increase the energy efficiency of the process or to improve the quality of the end products. Equally important is the cost of implementing this process. Significant investments are required for both initial expenses and additional materials. Despite the aforementioned problems, many organisations are actively researching, improving, and implementing various chemical recycling methods.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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