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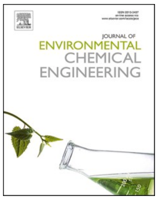

Hydrothermal processing for plastic waste valorisation: Technical pathways, environmental performance, and prospects for commercialisation

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ABSTRACT

Hydrothermal processing (HTP) is a promising solution to the global plastic waste crisis, integrating waste reduction, hazard mitigation, and resource recovery to advance the circular economy. Operating under high-temperature and high-pressure aqueous conditions, HTP transforms plastics into value-added products such as hydrochar, bio-oil, organic acids, and syngas. Different types of HTP technologies provide great potential for plastic waste valorisation, with several companies working to commercialise HTP plants fully; however, despite many advancements, HTP faces significant barriers to large-scale adoption, including high energy demand, complex system design, and economic feasibility concerns. This study highlights the environmental benefits of HTP, including reduced reliance on virgin resources and enhanced waste valorisation. Transparent communication among researchers, industry stakeholders, policy makers, and the public, supported by pilot demonstrations and cost-efficient strategies, is essential for broader societal acceptance of HTP systems. Enhancing energy efficiency through water recycling streams and process optimisation may enhance the economic costs associated with HTP systems. Furthermore, government support via subsidies and carbon credits will improve HTP's viability as a large-scale plastic waste solution, bridging the gap between laboratory success and commercial adoption.

1. Introduction

Plastic waste is a pressing global environmental issue, contributing to severe pollution, biodiversity loss, and potential human health risks, such as respiratory problems, endocrine disruption, and increased exposure to toxic chemical additives. Plastic's resistance and adaptable nature to various needs have made it a widely used material in many areas, including medicine, building, household appliances, and packaging. However, the qualities that make plastic so widely useful – its durability and low cost – also make it one of the most persistent pollutants when not adequately managed [1]. In 2024, global plastic waste production is expected to reach 220 million metric tonnes (Mt) annually, yet waste management remains a critical challenge [2,3]. Only 9 % of this global plastic waste is recycled, while 19 % is incinerated, and 50 % is landfilled, contributing to air, soil and water pollution [4]. Additionally, 22 % of plastic waste ends up in uncontrolled sites, posing severe environmental hazards [5]. Among the major contributors to plastic pollution are single-use plastics, particularly packaging, contributing up to 140 Mt (up to 40 %) of global plastic waste annually [6]. The predominantly discarded plastics within the packaging sector consist of polyethylene (PE), including its forms high-density polyethylene (HDPE) and low-density polyethylene (LDPE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS) [7,8]. When these materials enter the environment, they pose significant environmental and ecological challenges due to their persistence and resistance to degradation. Conventional plastic waste management methods, including landfilling, incineration, and recycling, have been widely implemented to address this growing issue.

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However, with the ever-increasing plastic problem, these waste management methods face significant environmental and commercial challenges [9]. Although landfilling and incineration are widely employed worldwide for economic convenience, both methods pose serious long-term environmental hazards. For instance, when contained in landfills, plastic waste gradually breaks down into microplastics (polymers with a diameter smaller than 5 mm), contaminating soil, water, and air. These microplastics act as carriers for toxic pollutants, including heavy metals and persistent organic pollutants, which can bioaccumulate in the food chain, posing risks to ecosystems and human health. Moreover, plastic degradation is an extremely slow process, often taking centuries, leading to long-term accumulation in landfills and surrounding environments. This persistent pollution can alter soil microbial communities, reduce agricultural productivity, and disrupt aquatic ecosystems [10]. Plastics occupy significant landfill space without breaking down, limiting the capacity for other types of waste, wasting valuable resources, and intensifying waste management issues [11].

Incineration, while reducing waste volumes effectively, generates harmful by-products like halogenated gasses, furans, dioxins, and polychlorinated biphenyls (PCBs), which can enter the atmosphere and endanger human health and ecosystems [12]. Burning halogenated plastics like PVC can generate hydrogen chloride (HCl) and other acidic gases, leading to acid rain and respiratory problems. Incineration contributes significantly to CO_2 emissions since most plastics are derived from fossil fuels. Long-term exposure to emissions from incinerators can lead to cancer, respiratory diseases, and developmental disorders, especially in populations living near facilities [11]. Moreover, incineration often results in toxic ash residues that require careful disposal to prevent further environmental contamination. Such risks have prompted countries like New Zealand to prohibit incineration, encouraging a shift toward alternative waste management methods [13]. As a result, recycling technologies such as mechanical and chemical recycling have been developed as more sustainable and economical alternatives to plastic waste management. For instance, mechanical recycling involves sorting, shredding, washing, and drying to repurpose plastic waste into new products. However, traditional recycling methods usually cause material degradation during recycling, producing lower-quality products. These methods require extensive sorting and cleaning and are limited to specific plastic types such as PE, PP, and PET, making them labour-intensive, costly, and selective [14]. Commonly, mixed plastics, or those contaminated with food, oils, or other substances, reduce the quality of the recycled material and increase sorting and cleaning costs associated with mechanical recycling [15]. Additionally, dyes and additives commonly used in plastics often make it difficult to achieve consistent product quality, limiting reuse options [11]. To overcome these limitations, chemical recycling technologies have become increasingly popular as they break down plastics into their monomeric forms that can be utilised to manufacture new plastic products. Unlike mechanical recycling, chemical recycling methods can process mixed or contaminated plastic streams found in landfills, often without extensive sorting and cleaning, offering greater flexibility in handling heterogeneous plastic waste [16]. However, these technologies (e.g. pyrolysis and gasification) can be energy-intensive and costly from an operational standpoint, requiring advanced equipment and additional pre-treatments to process persistent waste streams such as plastics efficiently [17]. Additionally, certain chemical reactions involved in these processes may release harmful byproducts, including dioxins and heavy metals, posing potential environmental and health risks.

Given these limitations, there is an urgent need for a more efficient and environmentally friendly plastic waste treatment method. Hydrothermal processing (HTP) has emerged as a promising alternative, offering significant advantages over conventional methods. Unlike mechanical and chemical recycling, HTP operates in a water-based environment at elevated temperatures and pressures, effectively breaking down a wide range of plastics, including mixed and contaminated waste streams, without extensive preprocessing. Additionally, similarly to chemical recycling methods such as pyrolysis, hydrothermal technologies facilitate resource recovery by converting plastics into valuable hydrocarbons, syngas, or other reusable chemical compounds, thereby reducing reliance on virgin plastic production [18].

As research in HTP continues to expand, its potential for revolutionising plastic waste management becomes increasingly evident. Hydrothermal technologies are classified into either oxidative or non-oxidative processes. Non-oxidative HTP technologies include hydrothermal carbonisation (HTC), which produces solid carbon-rich products between 150–350°C; hydrothermal liquefaction (HTL), which yields liquid fuels and platform chemicals between 250–550°C; and hydrothermal gasification (HTG), which generates gaseous products such as H_2 and CH_4 between 350–700°C. Oxidative HTP technologies involve a process known as hydrothermal deconstruction (HTD), which breaks down plastics into simpler chemical constituents such as acetic acid at temperatures between 150–350°C. These technologies have gained significant attention within the research community, showcasing their potential for development and implementation within the plastic waste management sectors. Fig. 1 showcases the advances and research trends within the field of different HTP technologies for plastic waste management since 2005. The data indicates rising popularity and, thus, a broader research potential in different HTP techniques for the treatment of plastic waste.

Despite the growing interest in HTP of plastic waste, significant gaps remain in the available literature. Table 1 summarises available reviews on HTP of plastics from Scopus and WoS databases. Several reviews discuss general degradation mechanisms for plastics but lack detailed mechanisms specified for each plastic type. While plastic degradation HTP processes have been explored beyond laboratory concepts, the degradation mechanisms remain under development on a full commercial scale for certain plastic materials. Additionally, Table 1 reflects how many studies fail to address the commercial feasibility, societal acceptance, economic viability, and environmental impact of these processes. This review integrates these multidisciplinary perspectives, making it valuable for researchers, policymakers, and industry stakeholders to fully understand the potential of these technologies.

2. Hydrothermal treatment technologies

Hydrothermal processing offers a sustainable solution for plastic waste valorisation by utilising a high-temperature and high-pressure aqueous environment to convert synthetic polymers into valuable products such as biochar, bio-oil, syngas, organic acids and solubilised

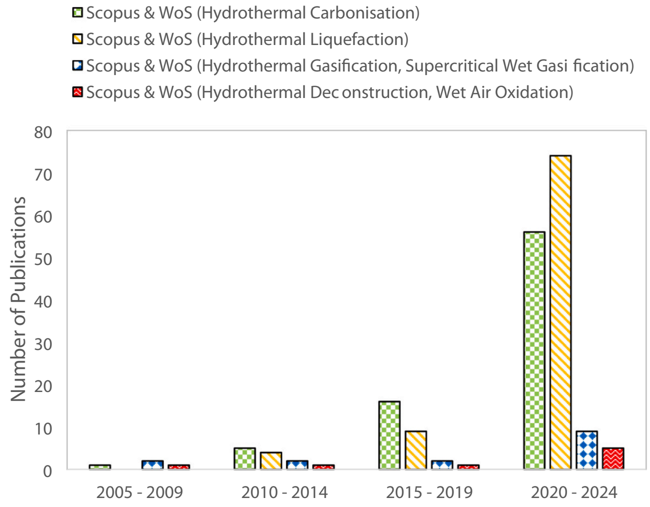


Fig. 1. Research trends since 2005 for HTP of plastic waste from the Scopus and Web of Science databases.

Table 1
Review articles on HTP of plastic waste currently available from Scopus and Web of Science databases.

Ref.	Review highlights	Required further work
[19]	Techno-economic overview of HTL technologies for LDPE waste	Societal acceptance analysis Process mechanisms for different plastic waste streams
[20]	HTC of various plastic materials Thorough analysis of the fundamental HTC mechanisms Effect of processing plastics when mixed with biomass (co-HTC)	Environmental impacts, societal acceptance, process economics, large-scale implementation, and the current technological standing
[21]	Mechanisms involved in HTG of plastic waste Reaction parameters and adjustment of syngas compositions for specific industrial applications	Evaluation of the HTG technology in terms of its technical, societal, environmental, and economic factors
[22]	Main mechanisms and kinetics of solid degradation	Plastic waste degradation Evaluation of the HTD technology in terms of its technical, societal, environmental, and economic factors
[18]	Applications of HTP for resource recovery Potential energy and value-added products Operational and technical applicability of HTP	Process mechanisms for various plastic waste streams
[23]	Comprehensive evaluation of HTC parameters Exploration of real-world applications and policy relevance Plastic decomposition mechanisms	Mixed plastic waste treatment evaluation Discussion of circular economy and environmental impacts Discussion of cost-effective innovations and large-scale deployment
[24]	Investigation of plastic degradation using HTL Discussion of various plastics behaviour under HTL conditions Discussion of environmental relevance and importance of the HTL process	Lacks cross-comparison of results across studies Detailed economic analysis of HTL process and its by-products Discussion of societal considerations towards large-scale implementation
[25]	Thorough discussion on environmental impacts of HTP Evaluation of HTP as a recycling method for plastics Discussion of HTPs alignment with circular economy principles	Discussion on optimisation of HTP operating conditions Reaction mechanisms of various HTP systems Economic viability and market analysis

carbon. Unlike conventional treatments, HTP can process wet feedstocks without pre-drying, making it more energy-efficient. In addition, the high-pressure aqueous systems facilitate the breakdown and separation of contaminants and impurities commonly found in plastic waste streams. For instance, impurities such as pigments and flame retardants typically partition into the aqueous phase or solid residue, allowing for easier separation post-processing while certain hydrothermal technologies are capable of fully destroying or detoxifying these problematic additives [26]. Depending on the operating conditions and target products, HTP is categorised into four main techniques (Fig. 2): hydrothermal carbonisation (HTC), hydrothermal liquefaction (HTL), hydrothermal gasification (HTG), and hydrothermal deconstruction (HTD) [18,22,27]. The following sections provide a comprehensive overview of each hydrothermal technology, highlighting their operational mechanisms and efficiency for degrading various plastics based on polymer solid reduction and by-product yields.

2.1. Hydrothermal carbonisation

Hydrothermal carbonisation (HTC) is a subcritical water treatment process that converts organic material, such as plastics, into a carbon-rich product known as hydrochar [28–31]. Hydrochar obtained through HTC is a solid, carbonaceous material with coal-like properties, typically exhibiting a high degree of aromaticity, oxygen functionality, and structural heterogeneity. It forms through a series of reactions under HTC conditions, which typically involve temperatures between 150–350 °C and moderate pressures (20–40 bar) in a non-oxidative, aqueous environment [28,30,31].

During HTC, polymers containing hydrolysable or reactive functional groups (e.g. ester or amide bonds) can break down into intermediate compounds that undergo further polymerisation and aromatisation into hydrochar. Unlike biomass, which readily undergoes carbonisation due to its high lignin, cellulose, and hemicellulose content, plastics exhibit variable behaviour in HTC due to their diverse chemical structures and bond stability.

In HTC, subcritical water facilitates polymer hydrolysis by breaking the hydrolysable bonds of specific polymers (e.g. ester bonds in PET), leading to terephthalic acid (TPA) and ethylene glycol (EG) formation (Eq. 1). Under HTC conditions, TPA can condense and polymerise into a carbon-rich hydrochar (Eq. 2) [30,32].

$$\mathrm{PET} + \mathrm{H_2O} \rightarrow \mathrm{TPA} + \mathrm{EG} \quad (1)$$

$$\mathrm{TPA} \rightarrow \mathrm{Hydrochar} + \mathrm{CO_2} + \mathrm{H_2O} \quad (2)$$

Other hydrolysable polymers include Polyurethanes (PU) and Polyamides (Nylon). They contain amide and urethane bonds, which hydrolyse under HTC conditions to form various intermediates that can participate in cross-linking and condensation to form hydrochar. The subsequent reaction conditions influence whether these intermediates condense into hydrochar or remain dissolved in the aqueous phase.

The reaction pathways, however, vary for different types of plastics. Polymers containing a saturated hydrocarbon backbone, such as PE and PP, are highly resistant to degradation in subcritical water (~180–250°C). At higher HTC temperatures (> 250°C), chain scission can occur, producing smaller hydrocarbons, waxes and oils [20]. However, these polymers primarily undergo physical breakdown, known as thermal degradation, due to the absence of hydrolysable bonds, producing limited to no hydrochar during HTC.

$$\mathrm{PE} + \mathrm{H_2O} \rightarrow \mathrm{Alkanes} + \mathrm{Alkenes} + \mathrm{Waxes} + \mathrm{Oils} \quad (3)$$

On the contrary, polymers like PVC follow a dehydrochlorination pathway, releasing HCl and forming a carbon-rich residue with aromatic condensation, as demonstrated in Fig. 3 [5,33]. Water-soluble volatile compounds are solubilised in the water and are often found in the aqueous phase of the product. At the same time, some intermediates undergo gasification and are released in the form of CO_2 and H_2. The hydrochar produced via plastic HTC may contain residual aromatic and aliphatic carbon compounds, depending on the type of plastic waste processed and the specific conditions of the HTC process [20,30].

Hydrochar, produced via HTC of plastic waste, has promising applications across energy, environmental, and industrial domains due to its versatile properties. As a solid fuel, plastic-derived hydrochar has a high energy content, making it suitable for combustion processes and heat and power generation [20]. Hydrochar derived from certain plastic materials, such as PET, for instance, can be further processed into activated carbon, used widely for environmental remediation and water purification, and as adsorbents for heavy metals and pollutants such as phosphorus from agricultural runoff [34,35]. Unlike traditional chars derived from pyrolysis of plastics, for instance, which tend to be more aromatic, carbon-rich and thermally stable, the HTC process allows for hydrochar with a slightly higher solid yield of up to 30–50 % and an overall improved energy efficiency [36–38]. However, hydrochars derived from plastic waste streams may retain organic compounds such as alkenes, amides, phthalates, and microplastic residues, potentially posing toxicity risks and requiring careful handling before being utilised within environmental sectors.

Additionally, plastic-derived hydrochar generally has a lower aromaticity than biomass-derived hydrochar due to plastics lacking the lignin content, which contributes to forming aromatic structures during HTC. However, plastic-derived hydrochar may exhibit a higher calorific

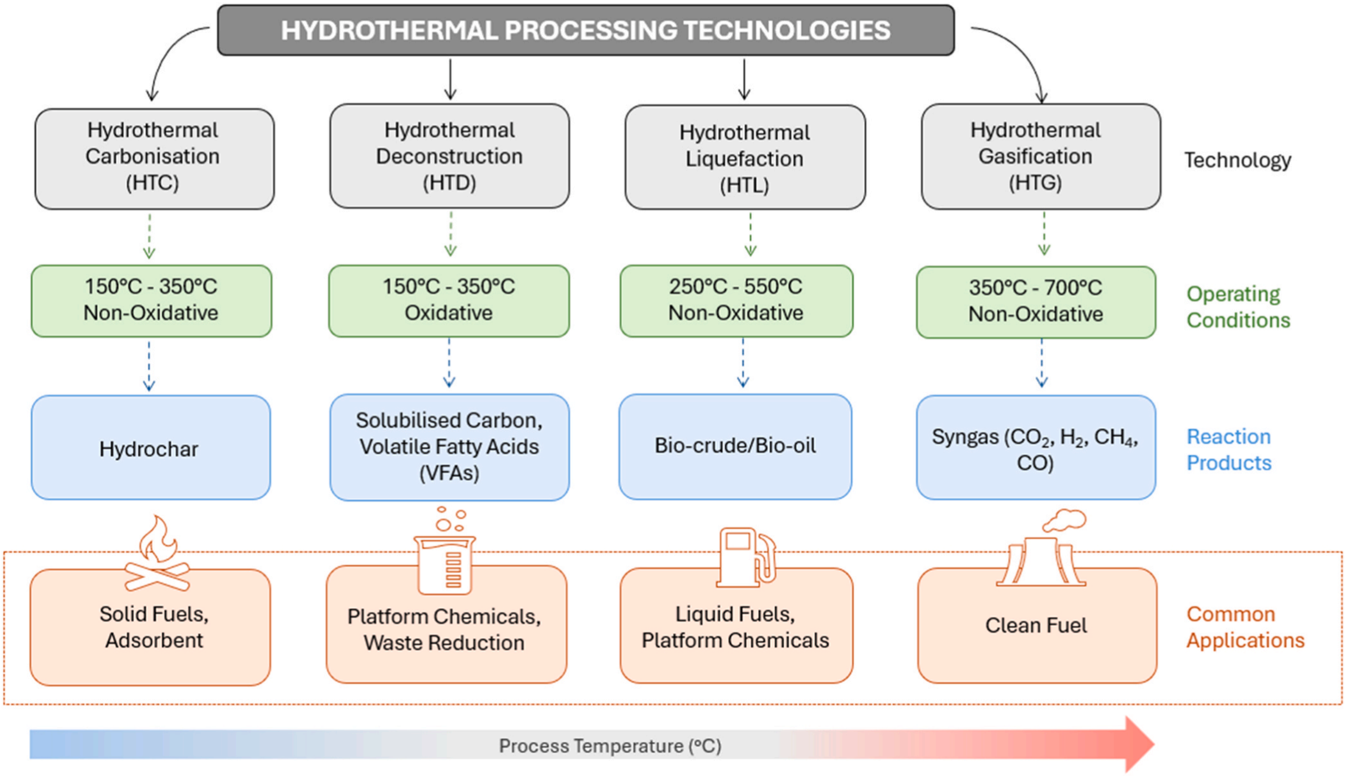


Fig. 2. Overview of available hydrothermal technologies, including their operational conditions, products obtained, and applications within industries.

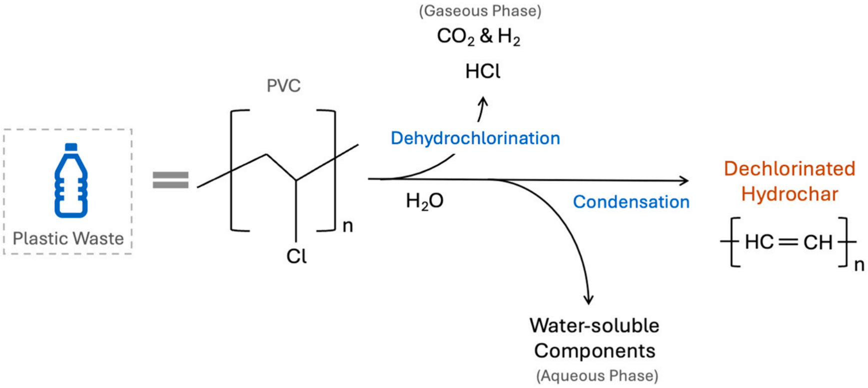


Fig. 3. Reaction mechanism of PVC molecule degradation into hydrochar under HTC conditions.

value of up to 21 % due to the energy-dense nature of some plastic materials, providing a more potent fuel source than biomass feedstocks [5]. Plastic provides hydrochar with a unique chemical composition, influenced by the polymerisation and degradation of polymers, resulting in enhanced reactivity during combustion. Multiple studies have explored mixing plastics with biomass during HTC (co-HTC) to improve hydrochar fuel properties and reduce harmful by-products, such as chlorinated compounds, enhancing its safety and efficiency [20]. Similarly, more conventional processes like co-pyrolysis are often utilised to produce char-like substances from plastic-containing feedstocks, similar to hydrochar. Co-pyrolysis typically leads to char containing higher aromaticity and more condensed structures, making it suitable for high-energy fuels and activated carbons [39]. Conversely, co-HTC produces hydrochars that retain more oxygen-containing functional groups and exhibit unique morphologies, making them advantageous for applications such as soil amendment and pollutant adsorption [20,40].

Furthermore, the HTC aqueous phase may contain dissolved compounds like phenols and residual oligomers, which can be further processed using anaerobic digestion (AD) to enhance methane production [41]. Additionally, recirculation of process water can mitigate water consumption. However, an untreated HTC aqueous phase may pose contamination risks due to leached microplastics, heavy metals, and toxic chemicals, necessitating treatment before disposal or reuse.

2.1.1. Plastic degradation efficiency of HTC

Recent research on plastic waste treatment using HTC, summarised in Table 2, shows selective effectiveness in processing polymeric feedstocks and emphasises the importance of the presence of reactive sites in the original polymer molecule. Reactive sites, often refer to specific structures or functional groups, such as heteroatoms (e.g. oxygen, nitrogen, chlorine) within the molecule that introduce polarity or weak points in the polymer chain and make the plastics prone to reacting under HTC conditions. For instance, chlorinated polymers such as PVC and polyesters such as PET show moderate reactivity when exposed

Table 2
Summary of recent studies performed on HTC processing of feedstocks containing different types of plastics.

Author	Feedstock	HTC Conditions	Hydrochar yield
[30]	PET, PS	T = 270–280°C Time = 30 min	PET = 65.1 wt% PS = 47.9 wt%
[32]	Sewage sludge, PET	T = 240°C Time = 120 min 20 wt% PET	72.4 wt%
[44]	PVC, Pine sawdust	T = 280°C Time = 60 min	Pine sawdust = 57.7 wt% PVC = 44.4 wt%
[42]	MSW - containing plastic (PE, PP)	T = 280°C Time = 120 min	No chemical reactions occurred on PE and PP
[43]	PVC	T = 240°C Time = 60 min	40.7–43.7 wt%
[48]	LDPE & water hyacinth	T = 200°C Time = 90 min 12 % LDPE feedstock	29.2 wt%
[47]	Microplastics in sludge (PP, PET, PE, PS, PA, PU)	T = 260°C Time = 60 min	PET, PS, PU & PA completely removed

under certain HTC conditions due to the presence of chlorine and oxygen atoms, respectively, within their polymer structure [42,43]. In their study, Che et al. [30] collected over 60 wt% hydrochar from PET, while Feng et al. [43] and Zhang et al. [44] collected over 40 wt% hydrochar from PVC under the same temperature (270–280°C). Additionally, PVC-based materials undergo dichlorination at temperatures above 235°C, releasing chlorine-containing compounds, and significantly reducing toxic by-products, such as dioxins [43,45]. This dechlorinated hydrochar, with improved combustion efficiency, has potential applications as a cleaner solid fuel in petroleum refining and energy production [46].

On the contrary, polyolefins, such as PP and PE, primarily undergo physical changes rather than chemical breakdowns due to their lack of reactive sites, leading to lower degradation rates under HTC conditions [42,47]. However, some studies have demonstrated that plastic degradation efficiency improves when polymers are processed as mixed waste streams, particularly in the presence of biomass, lowering operational temperatures needed for the production of hydrochar. This is attributed to synergistic effects, where biomass-derived acids and radicals enhance polymer breakdown, improving hydrochar yield and quality. For example, Ong et al. [48] observed up to 29 wt% hydrochar production from LDPE when mixed with water hyacinth at 200°C. Similarly, Ye et al. [32] observed an increase of up to ~20 wt% in hydrochar yield from PET at lower temperatures when combined with sewage sludge compared to PET alone, suggesting that organic matter facilitates depolymerisation.

Although HTC does not typically require catalysts due to the catalytic nature of subcritical water, acidic catalysts (e.g. sulphuric acid and citric acid) have been investigated to enhance polymer hydrolysis and increase hydrochar yields [30]. However, catalysts, such as calcium oxide (CaO) and hydrotalcite, can be utilised during HTC to enhance specific reaction pathways or alter the properties of hydrochar [28,32]. These catalysts are used to weaken the strong carbon-carbon bonds present in plastics like PE and PP, facilitating the breakdown of polymer chains and contributing to a more efficient plastic degradation. Additionally, CaO helps to neutralise acidic byproducts that can form during the HTC of certain plastics such as PVC, as it effectively absorbs hazardous compounds like HCl, preventing it from corroding the reactor or unwanted side reactions.

2.2. Hydrothermal liquefaction

Hydrothermal liquefaction (HTL) utilises moderate temperatures (250–550°C) and high pressures (up to 200 bar) in an aqueous phase to convert plastics into liquid bio-oil. Unlike HTC, which primarily produces solid hydrochar, HTL operates at higher temperatures and pressures, favouring the breakdown of polymeric structures into liquid hydrocarbons and oxygenated compounds [49,50]. This makes HTL particularly advantageous for plastic waste processing, as it enables the conversion of synthetic polymers into fuel-like products, reducing reliance on fossil-based crude oil. Additionally, the reaction often produces solid residue (char), an aqueous phase effluent, and off-gases, with additional applications in various industries [51].

In HTL, water acts as a solvent and reactant, facilitating multiple reactions such as hydrolysis, decarboxylation, and depolymerisation, depending on the polymer type. Under HTL conditions, water becomes a reactive non-polar medium with high miscibility in organics, enabling conversion of complex polymers into value-added products like bio-oil [52]. For instance, polymers with hydrolysable bonds, such as esters in PET, undergo a similar process to HTC, where high temperatures and pressures facilitate hydrolysis of the polymer, generating monomers and intermediates like TPA and EG (Eq. 4). Unlike HTC reactions, TPA decomposes further into benzene derivatives and CO_2 through decarboxylation due to harsher conditions provided during HTL (Eq. 5).

$$\mathrm{PET} + \mathrm{H_2O} \rightarrow \mathrm{TPA} + \mathrm{EG} \tag{4}$$

$$\mathrm{TPA} \rightarrow \mathrm{Benzene} + \mathrm{CO_2} \tag{5}$$

Similarly, nylon contains hydrolysable amide bonds that undergo a hydrolysis reaction where monomeric acids and amines are formed (Eq. 6). These reactions occur efficiently at moderate temperatures (~250–300°C) due to polar functional groups that readily interact with water.

$$\mathrm{Nylon} + \mathrm{H_2O} \rightarrow \mathrm{Monomeric\ acids} + \mathrm{NH_3} \tag{6}$$

In contrast, non-hydrolysable polymers, like PE and PP, undergo a different reaction pathway, breaking down primarily through thermal cracking and random chain scission at higher temperatures (>350°C), forming smaller hydrocarbons such as alkanes, aromatics, olefins, and paraffins (Eq. 7). Alkanes further hydrogenate into saturated hydrocarbons, contributing to bio-oil formation. These polymers show significant resistance to degradation due to their lack of reactive sites and strong C-C and C-H bonds, requiring harsher conditions for complete breakdown.

$$\mathrm{PE} + \mathrm{H_2O} \rightarrow \mathrm{Alkanes} + \mathrm{Aromatics} + \mathrm{Olefins} + \mathrm{Paraffins} \tag{7}$$

However, these polymers can interact synergistically with hydrolysable materials such as PET or biomass in co-liquefaction (co-HTL), where oxygenated intermediates enhance free radical formation and improve overall conversion efficiency [53]. In this case, water facilitates decarboxylation reactions where CO_2 is removed, while intermediate compounds, such as alcohols, acids, and phenols, undergo condensation and polymerisation to form heavier molecules that contribute to bio-oil as demonstrated in Fig. 4. The composition of bio-oil varies significantly with polymer type, where hydrolysable polymers like PET and nylon produce more oxygenated compounds due to their functional groups, while non-hydrolysable polymers like PE and PP yield hydrocarbon-rich oils [54]. The gases produced, while minor, often depend on the polymers produced, as more carbonaceous polymers like PE and PP contribute largely towards CH_4 production, while CO_2 is present in larger quantities when PET is processed.

Polystyrene (PS), another common plastic, undergoes depolymerisation as an initial step during HTL to form styrene monomers and benzene derivatives, contributing aromatic hydrocarbons to the bio-oil fraction (Eq. 8).

$$\mathrm{PS} + \mathrm{H_2O} \rightarrow \mathrm{Styrene\ monomers} + \mathrm{Benzene} \tag{8}$$

Polymers like PVC require dehydrochlorination as a primary reaction step, releasing HCl and forming carbonaceous residues (Eq. 9), which can lead to challenges in product usability and reactor corrosion.

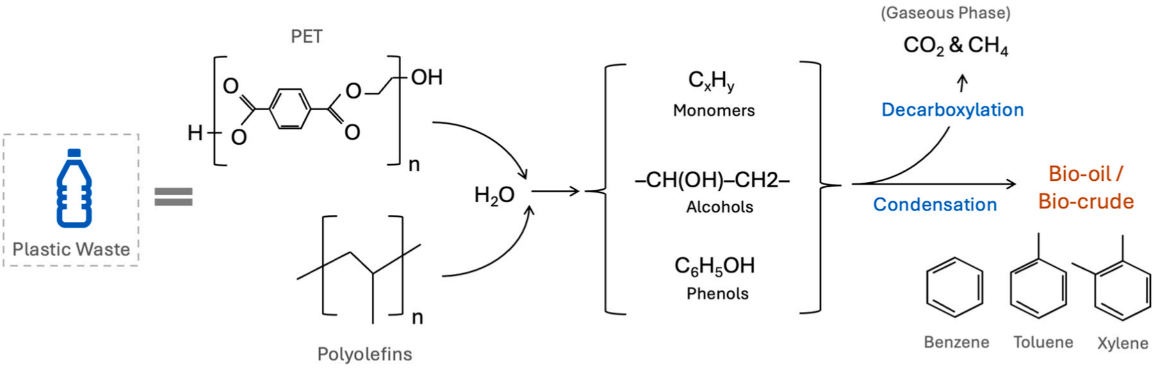


Fig. 4. Reaction mechanism of polymer molecule degradation into bio-oil under HTL conditions.

$$PVC + H_2O \rightarrow HCl + Aromatics + Alkenes \tag{9}$$

Water-soluble volatile compounds are often found in the aqueous phase of the product, while gaseous products predominantly include CO_2 (80–95 %) with small amounts of H_2, CO, and CH_4. The overall efficiency and selectivity of HTL depend on the polymer type, reaction conditions, and potential co-processing strategies [50,54].

The products obtained from the HTL treatment of plastics have diverse applications across several industries. Several studies highlight that bio-oil produced through this process yields many ready-to-use chemicals such as benzene, toluene, and xylene [53,55]. These chemicals are widely utilised in industrial applications such as producing certain plastics, synthetic fibres, and resins that can act as precursors for manufacturing various petrochemical products [50,53]. In addition, HTL-derived bio-oil from common carbon-rich plastics such as PE and PP has a high energy density and presents a promising alternative to conventional fossil fuels, contributing to a more sustainable waste-to-energy approach. However, despite its potential, bio-oil recovered from certain plastics, such as PET, often contains oxygenated compounds that can lead to instability, requiring further treatments to enhance the stability and usability in industries. These oxygenated compounds, such as acids, aldehydes, and ketones, contribute to high acidity, polymerisation, and phase separation, which degrade the fuel quality over time. Their presence increases the oil's corrosiveness and reduces its thermal stability, making it unsuitable for direct use in engines or refining processes. To improve bio-oil stability, various upgrading techniques can be applied, including hydrodeoxygenation (HDO), catalytic cracking, and esterification. These processes effectively remove oxygen by breaking down oxygenated functional groups, enhancing the oil's compatibility with conventional fuels and extending its storage life [56].

The gaseous products generated through HTL can be captured and repurposed for energy recovery [57]. The exact composition of these gases varies depending on the type of plastic feedstock used. Polyolefins, such as PE and PP, tend to generate higher amounts of CH_4 and H_2 due to their saturated hydrocarbon structures, favouring thermal cracking and hydrogen production. In contrast, oxygenated plastics like PET produce more CO_2 and CO because of their oxygen-containing functional groups, which undergo decarboxylation and decarbonylation reactions during HTL. Additionally, PVC decomposition releases HCl, which can contribute to catalyst deactivation and requires additional gas treatment steps. Gases such as CO_2 can be captured for industrial processes or collected and stored to mitigate greenhouse gas emissions and support the circular economy by enabling energy recapture, while methane, for instance, serves as an energy source or feedstock for producing chemicals like methanol [58]. Hydrogen, although present in smaller quantities, can also be extracted and utilised in refining processes or fuel cells, adding further value to the gaseous byproducts. By optimising process conditions, the gas yield and composition can be tailored to maximise energy recovery and minimise unwanted emissions. Additionally, the aqueous phase often contains organic acids, inorganic metals, alcohols, and ketones, which need to be treated before discharge to avoid potential environmental pollution. Consequently, the HTL aqueous phase is explored as a recycling stream throughout the HTL process on many lab-scale demonstrations, as it is thought to reduce water usage, wastewater treatment costs by reducing carbon discharge, and improve the bio-crude oil yields [59,60].

2.2.1. Plastic degradation efficiency of HTL

The HTL reaction is fundamentally dependent on reactive sites for hydrolysis in the original chemical structures of the polymers, similar to the HTC process [54]. Table 3 summarises the recent research on HTL of various polymeric feedstocks, comparing the amount of product yield obtained under specific HTL conditions and highlighting the significant variability in bio-oil yields depending on polymer type and processing conditions. Polymers containing hydrolysable bonds (PET, PS, and PVC) exhibit higher conversion efficiencies due to their heteroatom-rich structures, while polyolefins (PE, PP) require higher temperatures for depolymerisation. Furthermore, converting plastics such as PET, Nylon, polyurethane (PUR), and PVC into valuable monomers is only effective

Table 3
Summary of recent studies performed on HTL processing of feedstocks containing different types of plastics.

Author	Feedstock	HTL Conditions	Bio-oil yield
[54]	PE, PP, PS, PVC, PET	T = 340 °C P = 80 bar Time = 300 min Catalyst = NaOH	PE & PP = unreacted PVC, PET, PS = 7.7 wt %
[53]	HDPE, LDPE, PET, PC, PP, PS, PUR, PVC	T = 350 °C P = 200–240 bar Time = 20 min Catalyst = KOH	HDPE, LDPE, PP, & PS = ~5 wt% PC, PVC, PET = ~20 wt%
[55]	PS, PP, PE, PET, PC, ABS, PA	T = 450 °C P = 200 bar Time = 30 min	PC = 67.3 wt% PS = 93 wt% ABS = 76 wt% PA = 45 wt% PET = 10 wt% HDPE = 47.3 wt% LDPE = 76.9 wt% PP = 64.5 wt%
[61]	PE, PP, PET, Nylon – mixed with pistachio hulls	T = 350 °C P = 250 bar Time = 15 min	100 % biomass = 80 wt% 10 % PE, PP, PET, Nylon = ~80 wt% Mixed biomass and plastics = 90 wt%
[50]	MSW – containing plastic (PP, PC, PS, PET)	T = 300 °C P = 250 bar Time = 30 min	31.6 wt%
[49]	PE (HDPE) & PP	T = 480 °C P = 250 bar Time = 104 min	90.3 wt%

under optimal conditions (~350°C and 20 min residence time) [53,61]. Temperature stands out as a significant factor impacting the HTL efficiency of processing plastics. In their study, Ciuffi et al. [54] demonstrated that PE and PP only undergo physical changes, such as melting at temperatures around 340°C. However, Harisankar et al. [55] highlight that higher temperatures (above 400°C) are necessary to achieve significant bio-oil production from these plastics. In their study, bio-oil yields of up to 47 wt% for HDPE, 77 wt% for LDPE, and 65 wt% for PE were achieved at 450°C. This resistance significantly limits the efficiency of HTL for processing the most commonly discarded plastics in waste streams. The need for harsher conditions, such as elevated temperatures, not only requires stricter safety operating measures but also increases the energy consumption of the process itself [53]. Apart from temperature, other key parameters influence the HTL process, including reaction time, pressure, and the presence of catalysts and solvents. Passos et al. [53] explored the use of KOH and highlighted that the alkali environment provided by the catalyst favours a greater hydrolysis rate. For instance, when processing PET, there is a generally decreasing trend in solid residues from ~10 wt% to ~5 wt%, and an increase in aqueous phase yields from ~20 wt% to ~50 wt%.

Several studies investigated the interaction between plastic and biomass feedstocks to further improve bio-oil production, particularly when co-liquified [50,61,62]. They highlight the positive impact of mixed waste streams on improving oil yield by enhancing depolymerisation at lower temperatures than plastic alone. For instance, Harisankar et al. [55] observed only physical changes to PE and PP materials at 350°C in their study, while at 300°C, Seshasayee & Savage [50] recovered up to 31 % oil yield when these polymers were mixed with other biomass. This observation was similar to that of plastic decomposition under HTC conditions. Some studies indicate that HTL of mixed waste streams at subcritical conditions (e.g., 300–350°C) can produce bio-oil with favourable energy content, as the presence of plastics contributes to slightly higher oil yields when combined with organic matter [50,63].

2.3. Hydrothermal gasification

Hydrothermal gasification (HTG) utilises high temperatures (350–700°C) and pressures (210–300 bar) to convert plastics into syngas, consisting of H_2, CH_4, CO_2, and small amounts of CO [64,65]. This process can be further classified into subcritical HTG (350–500°C) and supercritical HTG (> 500°C), with subcritical conditions favouring higher CH_4 and CO yields, while supercritical conditions favour higher H_2 and CO_2 yields and full polymer breakdown [66]. Compared to pyrolysis and incineration, HTG offers higher energy efficiency and reduced emissions due to the unique properties of supercritical water, which enhances reaction rates and selectivity toward cleaner gas products.

The operational mechanisms of HTG for different plastic feedstocks are still under research and development owing to the complexity of the reaction itself. A study on HTG process optimisation by Okolie et al. [64] outlines that the reaction begins with the breakdown of polymeric chains into their respective monomeric components through thermal cracking. This step forms smaller hydrocarbon fragments, including oligomers, radicals, and monomers (Eq. 10).

$$\text{Polymer} + H_2O \rightarrow \text{Monomers} + \text{Oligomers} + R^{\bullet} \tag{10}$$

The smaller hydrocarbons undergo reforming (Eq. 11), water-gas shift (Eq. 12), and methanation (Eq. 13) reactions with supercritical water, leading to the production of syngas, primarily composed of H_2, CH_4, CO_2, and CO and other hydrocarbons. During this stage, unsaturated intermediates, such as alkenes and aromatics, are hydrogenated, producing saturated hydrocarbons or CH_4 and CO, while larger hydrocarbons undergo steam reforming to produce H_2 and CO_2, as illustrated in Fig. 5.

$$C_nH_m + \quad H_2O \rightarrow CO + H_2 \tag{11}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{12}$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O \tag{13}$$

These reactions rely heavily on temperature, pressure, feed concentration, and reaction time. Adjusting these parameters can favour certain reactions, altering the composition of syngas produced [64,67]. For instance, most studies on HTG report that lower temperatures (350–500°C) increase the production of CO and CH_4, whereas higher temperatures (500–700°C) result in higher amounts of H_2 and CO_2 [66]. Adjusting the operating conditions allows adjustment of syngas composition for specific applications, making HTG a versatile process for renewable gas industries.

Syngas produced via HTG is a versatile product, as demonstrated by its adjustable composition. For instance, H_2-rich gas is widely used in ammonia production (for fertilisers), refining processes, and as a clean fuel in hydrogen fuel cells for energy generation [68]. Methane, the primary synthetic natural gas component, can be used for power generation and as a precursor for chemical synthesis in industries [69].

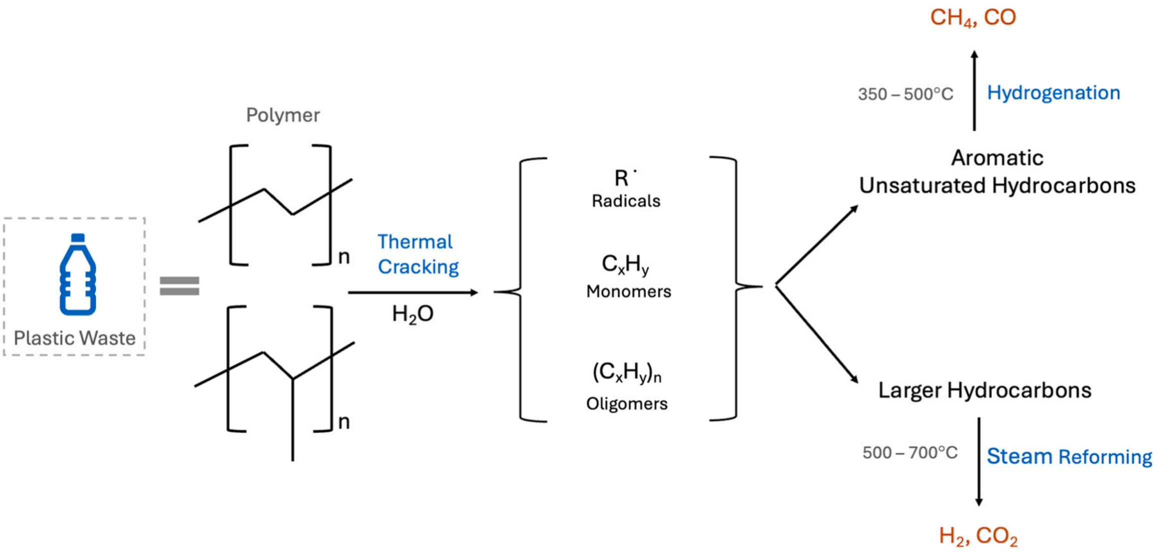


Fig. 5. Reaction mechanism of polymer molecule degradation into syngas under HTG conditions.

Additionally, CO_2 can be captured and used in carbonation processes and as a feedstock for chemical industries. Separation and purification of syngas components through membrane separation, cryogenic distillation, and absorption techniques are used to extract high-purity H_2, CO_2, and CH_4 and increase their usability in industry [70].

The composition of syngas varies depending on the type of plastic feedstock processed. Polyolefins, such as PE and PP, tend to produce syngas with higher CH_4 and CO content due to their high carbon-to-hydrogen ratios and lack of oxygen in the polymer backbone. In contrast, oxygen-containing plastics, such as PET and PC, yield more CO_2 and H_2 due to the presence of oxygen, which enhances water-gas shift reactions. Plastics containing aromatic structures, such as PS, often lead to the formation of higher concentrations of benzene derivatives and CO during HTG processing. However, syngas produced via HTG of plastic waste may contain contaminants such as tar, particulates, sulphur and nitrogen compounds, halogens, and trace metals, which may cause fouling of equipment, catalyst deactivation, erosion, and environmental pollution. These impurities must be removed through advanced gas cleaning techniques like adsorption, catalytic reforming, and wet/dry scrubbing to produce high-purity syngas suitable for use as chemicals and fuels. Along with a gaseous product, the HTG reaction often produces small amounts of a liquid effluent containing organic acids, alcohols, and other soluble compounds that may be recovered and used in chemical production or wastewater treatment [66].

2.3.1. *Plastic degradation efficiency of HTG*

Notably, research on HTG has shown promising results for valorising animal manure [71], sewage sludge [72], food waste [67], and leachate from municipal solid wastes and landfills [73] due to their high moisture levels. However, currently, minimal research focuses on exploring HTG as a potential technology to treat plastic materials. Table 4 summarises the notable research within this field and highlights that the composition of syngas from HTG is highly dependent on the plastic feedstock and reaction conditions. For instance, Türker Üzden et al. [74] highlight that PET yields higher CO_2 and H_2 contents due to its oxygen-rich structure, while Onwudili & Williams [75] and Yildirir et al. [76] show that polyolefins (PE and PP) favour CH_4 formation due to their saturated hydrocarbon backbone. Additionally, a few studies summarised in Table 3 exploring HTG processing of plastics emphasise the importance of temperature, reaction times, and catalysts for obtaining the most desirable product. Higher temperatures increase the rate of thermal cracking and water-gas reactions, leading to faster polymer breakdown into smaller hydrocarbons and gases. As observed in Table 4, higher temperatures (> 500°C) lead to a product consisting mainly of H_2 and CO_2, while lower temperatures (< 500°C) favour CH_4 production. Most plastics require temperatures above 350°C for effective degradation, while 500–600°C is optimal for complete gasification in supercritical water. However, studies highlight that excessively high temperatures (> 600°C) may lead to excessive energy input, reducing the net energy efficiency of the process. In contrast, lower temperatures (between 350 – 500°C) can result in incomplete conversion or the formation of liquid and solid residues. Additionally, longer reaction times (> 60 min) allow for more complete polymer breakdown and secondary reactions. In comparison, shorter reaction times (< 30 min) may lead to the accumulation of intermediates, such as liquid hydrocarbons, tars, or char.

A common observation among many studies on HTG of plastic waste is the positive effect of catalysts. Catalysts lower the activation energy of reactions, accelerating the breakdown of plastics and improving gas yields even at lower temperatures. Catalysts such as Ru-based materials are discussed to promote faster decomposition of polymers and reforming hydrocarbons into syngas components [76]. Their presence enhances selectivity toward desirable gaseous products like H_2 and CH_4 by promoting steam reforming and methanation reactions. A study performed by Onwudili & Williams [75] indicated that up to 33 wt% of a gaseous product was produced when a catalyst was absent at 500°C, while in the presence of RuO_2, up to 95 wt% of the gas product was obtained at lower temperatures (under 450°C). In contrast, while Ni-based materials are thought to encourage gas formation during HTG, their presence is not as effective as that of Ru-based materials. This is seen in a study done by Morais et al. [77], showing that with Ni-based materials, only 21 % of PP was converted to gas with the best performing catalyst under 350°C.

Table 4
Summary of recent studies performed on HTG processing of various feedstocks.

Author	Feedstock	Conditions	Gas Product	
			wt %	Main Component
[74]	PET	T = 500 °C P = 250 bar Time = 30 min No catalyst	28	H_2 & CO_2
[75]	LDPE, HDPE, PP and PS	T = 450 °C P = 380 bar Time = 60 min Catalyst = 20 wt % RuO_2	95	CH_4
[75]	LDPE, HDPE, PP and PS	T = 450 °C P = 380 bar Time = 60 min No catalyst	33	CH_4
[78]	ABS microplastics	T = 750 °C P = 230 bar Time = 60 min No catalyst	45	H_2 & CO_2
[76]	Carbon fibre-reinforced plastic wastes	T = 500 °C P = 240 bar Time = 30 min Catalyst = Ru/Al_2O_3	75	CH_4
[77]	PP	T = 350°C P = 200 bar Time = 60 min Catalyst = I-Ni	22	H_2

2.4. *Hydrothermal deconstruction*

Hydrothermal deconstruction (HTD), also known as wet air oxidation (WAO), is another hydrothermal process that decomposes complex organic waste materials, including plastics, into simpler molecules. The process operates at moderate temperatures similar to the HTC process (150–350°C) and pressures between 5–200 bar [79–81]. However, unlike the hydrothermal processes discussed previously, HTD operates in the presence of oxygen to effectively break down organic structures, including synthetic polymers, into simpler components such as H_2O, CO_2, and short-chain organic acids (mainly acetic acid) [81,82]. This makes HTD a highly efficient process for treating complex, mixed plastic waste streams while generating valuable chemical byproducts.

During the process, polymer molecules undergo oxidation (Eq. 14), reacting with oxygen to break down into more stable carboxylic acids like acetic acid. Free carbon (•C) and hydroxyl (•OH) radicals are then further oxidised into CO_2 and H_2O, as illustrated in Fig. 6 [83].

$$(C_xH_y)_n + O_2 \xrightarrow{H_2O} CO_2 + H_2O + \text{Organic acids}(\text{e.g.}, CH_3COOH) \tag{14}$$

Commonly, molecular oxygen from the air or in its pure form is used as the oxidant in this process [81,84]. The gas composition released during HTD is heavily dependent on the types of plastics processed, as halogenated plastics like PVC may release chlorine (Eq. 15), while amides may contribute to the formation of ammonia (NH_3) during oxidation (Eq. 16).

$$(C_2H_3Cl)_n + O_2 \xrightarrow{H_2O} CO_2 + H_2O + CH_3COOH + HCl \tag{15}$$

$$(C_6H_{11}NO)_n + O_2 \xrightarrow{H_2O} CO_2 + H_2O + CH_3COOH + NH_3 \tag{16}$$

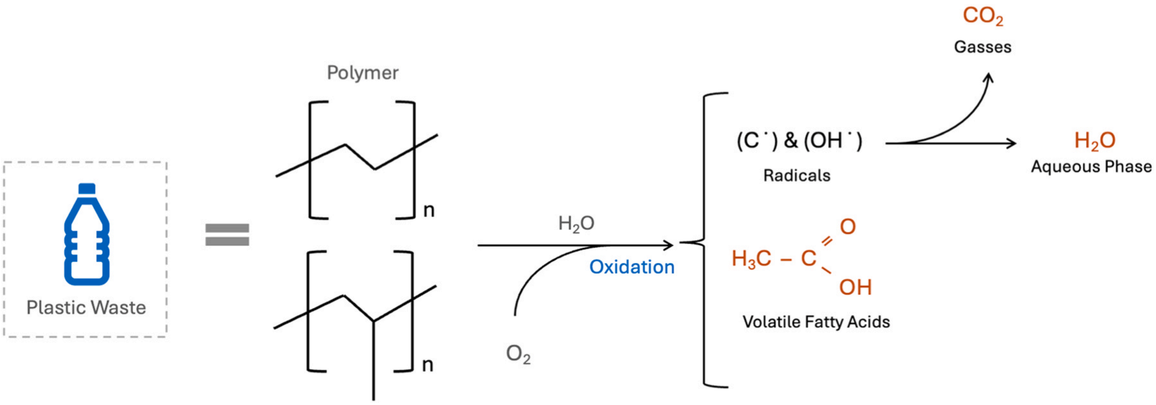


Fig. 6. Reaction mechanism of polymer molecule degradation into volatile fatty acids (VFAs) under HTD conditions.

Oxidation efficiency depends on factors such as temperature, pressure, and oxygen availability. The oxidation kinetics can be improved by increasing the oxygen-to-substrate ratio, which enhances the breakdown of persistent polymers.

The HTD by-products have distinct applications across chemical manufacturing, water treatment, and environmental management, supporting sustainable industrial practices. Carbon dioxide is often safely released as a non-toxic gas or captured in various industrial processes, as mentioned for CO_2 collected from other HTP systems [66]. In HTD systems, however, CO_2 capture can occur through gas separation techniques like membrane separation, adsorption, or chemical absorption using alkaline solutions to form stable carbonates, which can be recovered for sequestration or industrial applications.

Treated water from HTD is often purified and reused within industrial facilities for cooling or cleaning, effectively reducing water demand and supporting water conservation. Additionally, the process water can be recycled back into the HTD process and reused as a reaction medium, reducing the additional costs and energy requirements that result from using freshwater streams. Plastics with oxygen-containing functional groups, such as PET, readily produce organic acids like acetic, formic, and lactic acids during HTD, which can be recovered through phase separation, electrodialysis, or solvent extraction for use in the chemical industry to manufacture polymers (e.g., polyvinyl acetate in adhesives and coatings), synthetic fibres, and as a food preservative in the form of vinegar [79]. The ability to recover these acids not only enhances resource efficiency but also supports the economic viability of HTD by generating marketable by-products.

2.4.1. Plastic degradation efficiency of HTD

Compared to previously discussed hydrothermal technologies, HTD shows the highest efficiency at deconstructing synthetic polymers, as seen in Table 5. A study by Javid et al. [85] on wet air oxidation of personal protective equipment (PPE) shows up to 98 % solid waste reduction at temperatures above 250°C. The feedstock in this research included a mixture of several synthetic polymers such as PE, PP, PUR, PS, PC, and PVC [85]. When compared to studies performed on other organic feedstocks such as municipal solid waste streams, pharmaceutical waste, activated sludge, and cellulosic fibres, the deconstruction efficiency under HTD conditions seems relatively similar to that of plastic waste, where solid waste degradation reaches over 90 % [22,79,86–88]. Additionally, many of these studies observe higher yields of volatile fatty acids (VFAs), especially acetic acid, in the presence of synthetic polymers.

Materials known to contain certain plastics, such as PC, commonly show slight resistance to the HTD process. Javid et al. [85] indicated that for the deconstruction of PC-based materials, the solid reduction was only 55.6 % at 250°C, while at 350°C, it reached deconstruction of 97.6 %. The polymer undergoes a slow melting process due to the two large methyl side groups and a rigid polymer chain, requiring higher temperatures for breaking the polymer bonds. While there is a lack of research on utilising catalysts for HTD of plastic waste, there are several indications that the presence of a catalyst may enhance HTD conditions. Several articles explore the theoretical effect catalysts would have on general organic feedstock deconstruction and product yield under HTD conditions, stating that a catalyst would increase the oxidation rate of plastic molecules, shorten the reaction time, and allow for less harsh reaction conditions [90,91].

Table 5
Summary of recent studies performed on HTD processing of feedstocks containing different types of plastics.

Author	Feedstock	HTD Conditions	Acetic acid yield
[79]	MSW - containing PET, PP, PE	T = 280 °C P = 35 bar Time = 45 min	PET = 1000 mg/L PP = 1500 mg/L PE = 1000 mg/L
[85]	PPE (containing PE, PP, PET, PUR, PS, PC)	T = 300 °C P = 30 bar Time = 90 min	Up to 9000 mg/L
[80]	Microplastics (PE, PS, PET)	T = 240 °C P = 20 bar Time = 120 min	PEMPs = 1500 mg/L PSMPs = 1500 mg/L PETMPs = <100 mg/L
[89]	PP	T = 200 °C P = 30 bar Time = 560 min	2000–4000 mg/L

3. Evaluation of hydrothermal technologies

Unlike traditional plastic waste treatment methods such as incineration, landfilling, and mechanical recycling, hydrothermal technologies offer a unique advantage in processing mixed and contaminated plastic waste. However, challenges remain in scalability, process efficiency, and market competitiveness, necessitating a comprehensive assessment of their technological and societal readiness level (TRL and SRL, respectively). Additionally, environmental impacts were thoroughly assessed, and a comprehensive economic feasibility evaluation was performed to gauge the environmental and commercial potential of HTP systems. Table 6 summarises a comparison between different plastic waste management technologies.

Table 6
Comparison of plastic waste management technologies.

	TRL*	SRL*	Environmental Impact	Economic Assessment**	Ref.
Landfilling	High	High	High	Moderate	[92,93]
Incineration	High	High	High	High	[93,94]
Pyrolysis	Moderate	High	Moderate	Moderate	[18,95,96]
Conventional Gasification	High	Moderate	Moderate	High	[18,95]
Mechanical Recycling	High	High	Low	Low	[18,93,97]
HTC	High	Moderate	Low	High	[98–100]
HTL	High	Moderate	Moderate	High	[98–100]
HTG	Moderate	Moderate	Moderate	High	[98,100,101]
HTD	Moderate	Moderate	Low	High	[98,100,102]

* Low (1–3), Moderate (4–6), High (7–9).

** Economic assessment covers the overall operational and capital costs associated with the technologies.

3.1. *Technological readiness level*

The technology readiness level (TRL) system is a scale developed by NASA to assess a technology's maturity during its development, ranging from theoretical principles at TRL 1 to fully operational, commercialised systems at TRL 9 [103]. Recent assessments of hydrothermal technologies indicate that HTP systems generally hold an estimated TRL of 6–7, indicating that while these technologies have been successfully demonstrated at pilot scale, further development is required for full industrial adoption [98,104,105]. This estimate particularly applies to technologies such as HTG, which remains predominantly at the pilot stage and still requires substantial research and technical refinement. In contrast, HTC and HTL have demonstrated notable progress, with an increasing number of fully operational plants emerging in recent years, justifying an elevated TRL of 8. Similarly, HTD has shown significant advancements, achieving a TRL of 7–8, supported by the commissioning of several full-scale facilities. More conventional waste treatment methods, such as incineration, landfilling, and mechanical recycling, as summarised in Table 6, have reached a TRL of 9 due to their widespread implementation and established infrastructure [93]. Other conventional waste-to-energy and resource recovery technologies, such as pyrolysis and conventional gasification, are generally considered at TRL 8, with some commercial-scale applications but still undergoing optimisation for broader deployment [18,95].

Despite extensive research, industrial implementation of hydrothermal processing still faces challenges, particularly for hard-to-recycle waste streams such as plastics. Table 7 highlights growing industry interest in hydrothermal technologies. Companies like Teranova Energy (Germany), Ingelia (Spain), and HTCycle (Germany) have successfully commercialised HTC for biowaste treatment but have yet to reach larger-scale operations for plastic waste. Similarly, Licella, located in Australia, and Silva Green Fuel, located in Norway, have developed HTL processes for forestry and agricultural waste. Licella also advances plans for a large-scale HTL facility to treat end-of-life plastics and is in the process of developing this idea at a pilot scale. Additionally, companies like Scion and Veolia successfully developed HTD plants for processing sewage sludge in New Zealand and China, respectively, while companies like Nurox Hydrothermal, a New Zealand-owned company, are in the process of developing a commercial HTD plant for hazardous waste streams, including plastics.

However, while HTL, HTC, and HTD have almost entirely reached a fully commercialised scale, resulting in their high TRL ranking, most HTG projects have yet to advance past pilot plant operations due to the complexity of the process and lack of research around HTG systems. However, the incentives of several organisations show promise of an increase in the TRL ranking of HTG technology. For instance, GRTgaz, a French-owned company, is currently operating a pilot plant for the HTG of agricultural wastes, with plans to achieve full commercialisation in 2025. Similarly, TeraTech has developed an operational HTG pilot plant, located in the United States, for sewage sludge feedstocks and is working on plans towards wider commercialisation.

3.2. *Process optimisation and scale-up challenges*

While companies and organisations are looking into developing and implementing hydrothermal technologies to promote a more promising alternative to plastic waste treatment, several technical challenges still hinder the complete optimisation of this technology on a commercial scale [18].

3.2.1. *Energy efficiency and sustainability concerns*

Ensuring energy efficiency remains crucial, as these systems operate at elevated temperatures and pressures, requiring substantial energy input to maintain the necessary conditions of HTP systems. For instance, carbon-dense polymers like PS often require harsher conditions and thus are more energy-intensive and less efficient compared to oxygen-containing polymers like PET [30]. Polymers like PET are seen to recover up to 89 % energy yield, while PS is seen to only recover around 55 % energy yield from an HTC process [30,118].

If not appropriately managed, high energy demands can lead to high

Table 7
Summary of companies involved in commercialising hydrothermal technologies for the treatment of various feedstocks.

Company (Technology)	Feedstock	Current Scalability Level	Capacity	Ref.
TeraNova Energy (HTC)	Sewage Sludge & biowaste	Operational since 2016	14,000 t/year	[106]
Ingelia (HTC)	MSW, sewage sludge, agro-forestry, & food residues	Operational since 2012	78,000 t/year	[107]
HTCycle (HTC)	Biomass & sewage sludge	Operational since 2018	8000–16,000 t/year	[108]
Arbios Biotech (HTL)	Biomass from forestry	Scheduled for operation by 2024	25,000 t/year	[109]
Silva Green Fuel (HTL)	Forest & Wood residues	Under commercial test period	4000 L/d	[110]
Licella (HTL)	End of life plastics	Under-development	Unknown	[111]
Licella (HTL)	Wood, agricultural residue, pulp & paper	Operational since 2012	10,000 t/year	[111]
GRTgaz (HTG)	Sludge, agricultural residues, industrial effluents.	Pilot plant (expected to reach industrial scale by 2025)	6 t/h	[112]
TreaTech (HTG)	Sewage sludge	Pilot plant operational	100 kg/h	[113]
Terax / Scion (HTD)	Sewage biosolids	Pilot-plant operational	200 L/h	[114]
Nurox Hydrothermal (HTD)	Hazardous organic waste (eg. medical & plastic waste)	Under-Development	6500 t/year	[115]
Athos / Veolia (HTD)	Organic sludge	Operational since 2006	70–80 t/day	[116]
General Atomics (HTD)	Per-and polyfluroalkyl (PFAS) substances	Operational since 2012	Unknown	[117]

operational costs and increased carbon footprints. Heat integration and recovery strategies, such as capturing and reusing heat from hot effluents and vapours, are an effective solution towards minimising energy losses during the process. Renewable energy sources such as wind and solar can reduce the dependency on fossil fuels and contribute to lower greenhouse gas emissions associated with the high energy use of HTP systems.

3.2.2. Reactor durability and corrosion issues

The durability of reactor materials plays a significant role in determining system longevity and operational efficiency, and safety, as material degradation can alter heat transfer properties, impacting reaction kinetics, product yields, and personnel operating the reactor. Corrosion, thermal stability, and high-pressure endurance are substantial concerns, as aggressive reaction environments can degrade materials over time, leading to reactor failure [119,120]. Additionally, corroded materials can leach metal ions into the reaction medium, potentially contaminating the final products. Due to the extreme conditions under which these reactors operate, a failure in durability—whether from material degradation, wear and tear, or a design flaw—is a direct and serious safety risk that can result in an uncontrolled release of energy and hazardous materials, harming those within the vicinity of the reaction.

Exploring alternatives such as superalloys, ceramic coatings, and corrosion-resistant steels is essential to improving reactor lifespan, reducing maintenance costs, and ensuring reliability and safety during operation [121].

3.2.3. Catalyst deactivation and process efficiency

With some HTP technologies relying on catalytic activity for efficiency in plastic breakdown, catalyst stability remains a significant issue. Catalysts may experience deactivation due to sintering, fouling, and leaching under hydrothermal conditions, limiting the process efficiency and economic feasibility [120,122]. Research into novel catalytic materials, including transitional metal oxides, carbon-based supports, and zeolites, could contribute to more resilient catalytic systems sustaining prolonged operational cycles [123].

3.2.4. Lack of standardisation and data reproducibility

A significant limitation of hydrothermal technologies is the absence of standardised process parameters such as temperature, pressure, and residence time across different studies, making the scalability and the design of these technologies particularly demanding [18]. Without standardising these parameters, inconsistencies arise with variability in reactor configurations, operating conditions, and feedstock compositions when transitioning the technology from lab-scale operation to full commercialisation. Additionally, designing efficient batch and continuous systems for various feedstocks remains a barrier due to the heterogeneous and complex nature of HTP systems, inhibiting reliable process predictions and making scale-up costly and time-consuming [124]. Establishing universal benchmarks for reaction parameters, product characterisation, and system performance is essential to facilitating technology transfer and industrial adoption. Exploration of simulation models and utilising tools such as Aspen HYSIS could provide a robust framework for understanding the intricate reaction kinetics and thermodynamic behaviours of plastics under HTP conditions, as they allow for precise tuning of operational parameters to maximise product yields and conversion efficiencies. These tools would assist with developing standardised methodologies and process guidelines, which would reduce uncertainties and ensure reproducibility in hydrothermal processing applications.

3.3. Environmental analysis

Hydrothermal technologies offer an environmentally innovative approach to plastic waste disposal as opposed to traditionally utilised treatment methods. Table 8 provides a comparative summary of advantages and disadvantages between hydrothermal technologies and conventional waste treatment methods in terms of their hazard removal ability, value recovery potential, waste generation during processing, energy requirements, and CO_2-equivalent (CO_2-e) emissions.

Hydrothermal technologies demonstrate a high hazard removal efficiency due to their unique ability to significantly reduce the hazardous chemicals from certain polymer waste streams [33,127]. Plastics often contain halogens that, when released, can dissolve in water to form corrosive acidic compounds such as HCl or ammonia [5,30]. These compounds not only corrode reactor systems but also contaminate waste streams and can pose severe environmental risks to ecosystems. Recent research advancements include hydrothermal technologies combined with supercritical fluids or neutralising agents to safely extract hazardous halogens and other plastic additives from plastic-containing municipal solid waste [128]. Similarly, unfavourable hydrothermal conditions may result in incomplete plastic degradation, which may cause higher unreacted plastic yields and the presence of inorganic impurities. Often, this may lead to a complex aqueous phase rich in organic acids, phenols, and lower quality, heavier oil or tar. In many cases, incomplete hydrothermal polymer reactions may lead to less desirable gas compositions, potentially containing corrosive acid gases that may harm the environment when released into the atmosphere. However, careful handling of these waste streams and additional post-treatment are often required to prevent environmental harm [25,129]. Although HTP is particularly useful for high moisture feedstocks, polymers contain negligible moisture, and thus, the addition of large

Table 8

Comparison of the environmental impacts of HTP and other conventional plastic waste treatment methods.

Treatment Technology	Hazard Removal	Value Recovery	Waste Generation *	Energy Requirement** (MJ/kg plastic)	CO_2-e (kg CO_2-e/kg plastic)	Ref.
Landfilling	Low	Low	High	~ 1.0	~1.8–2.5	[18,92]
Incineration	High	Low	Moderate	~ 2.6	~ 3–4.6	[92,94]
Pyrolysis	High	High	Moderate	~ 2.5–4.5	~ 2.5–3.9	[96,125]
Conventional Gasification	High	High	Low	~1.5–3.5	~0.7	[18,126]
Mechanical Recycling	Low	Moderate	Low	0.6–1	~1.0–1.5	[96,97]
HTC	Moderate	High	Moderate	~2.8–3.5	~ 0.3–0.5	[18,99]
HTL	High	High	Moderate	~3–5	~ 0.5–1.0	[18,99]
HTG	High	High	Low	~ 4–6	~1.5–2.0	[21,101]
HTD	High	High	Low	~ 3–4	~1.0	[82,102]

[*] Waste generation refers to the amount of waste stream (e.g. solid or liquid) generated during the process. This value is specific for plastic feedstocks.

[**] Energy requirements depend on reaction conditions, reactor design, and feedstock properties; actual values may vary. Additionally, these values only reflect the energy required for processing. Additional energy requirements from upstream (e.g. collection or transport) are not included.

water quantities is required to create an efficient reaction medium. The significant volume of water required for HTP of plastics raises concerns regarding large-scale water consumption as it may deplete natural water sources, contributing to soil and habitat degradation, harming ecosystems and wildlife [25]. A key strategy explored in research to reduce the environmental strain of the high-water demands is recycling the process water, which is shown to significantly increase product yields while also alleviating the toxicity of the unreacted products.

Additionally, certain hydrothermal technologies like HTD have the potential to significantly reduce the chemical oxygen demand (COD) of wastewater streams. For instance, Javid et al. [85] reported that HTD can detoxify single-use personal protective equipment (including plastics) by significantly reducing COD levels by up to 94.8 % at 350 °C, contributing to a cleaner waste stream and less strain on environmental systems.

Moreover, a common feature all hydrothermal technologies share is their ability to recycle hard-to-treat plastic materials effectively and convert them into value-added chemicals, thereby reducing dependency on virgin feedstock [5,30]. Hydrothermal technologies are known for their effectiveness in value recovery due to the diverse range of byproducts, such as bio-oils, syngas, and organic acids, which support circular economy strategies, providing opportunities for safer waste-handling schemes. For instance, Jin et al. [130] used hydrothermal processing to valorise PE waste into fuels, naphtha, and wax. They indicated that the products obtained qualified similarly to the thermochemical properties of diesel and gasoline blendstocks. Similarly, Seshasayee and Savage [131] utilised hydrothermal technologies to convert PET, PP, PS, and PC into fuels that contain compounds suitable for polymer synthesis. They identified that the oil from these plastics contained bisphenol-A as a primary product, commonly used in manufacturing plastics and other polymeric materials, opening up the potential for the circularity of plastic waste using hydrothermal technology. Additional studies on hydrothermal treatments of various polymeric waste streams further supported this observation [53,100,132]. Similarly, beyond fuel production, acetic acid is a valuable chemical traditionally derived from petroleum. Acetic acid obtained through HTD of plastic materials provides several advantages over fossil-based production, including lower carbon emissions, reduced reliance on crude oil, and an opportunity to upcycle plastic waste into high-value chemicals.

Unlike conventional recycling, which is limited by contamination, hydrothermal techniques can handle mixed, multilayered, and contaminated plastics without extensive sorting or pre-treatment. However, additives or fillers, such as dyes, flame retardants, and plasticisers, can negatively affect hydrothermal reactions. These substances may interfere with the reaction kinetics, reduce process efficiency, or lead to the formation of toxic or environmentally harmful byproducts, posing challenges for downstream purification and reuse of recovered materials. Since these processes operate in a controlled, water-based environment, there is minimal release of harmful pollutants such as dioxins that are commonly associated with incineration. However, as Table 8 highlights, the HTP of plastic waste often demands higher energy requirements to maintain the high temperatures and pressures required for efficient plastic conversion. As a response, integrating heat recovery strategies, such as using heat exchangers or reusing process heat, can help reduce energy use. Additionally, catalytic enhancement can lower the required temperature and pressure, improve reaction efficiency, and reduce the formation of unwanted byproducts, making the process more energy-efficient overall. Despite high energy requirements, HTP systems generally produce lower CO_2 emissions compared to other plastic waste treatment methods, such as pyrolysis, as they avoid direct combustion processes and often have higher carbon retention in the liquid or solid products.

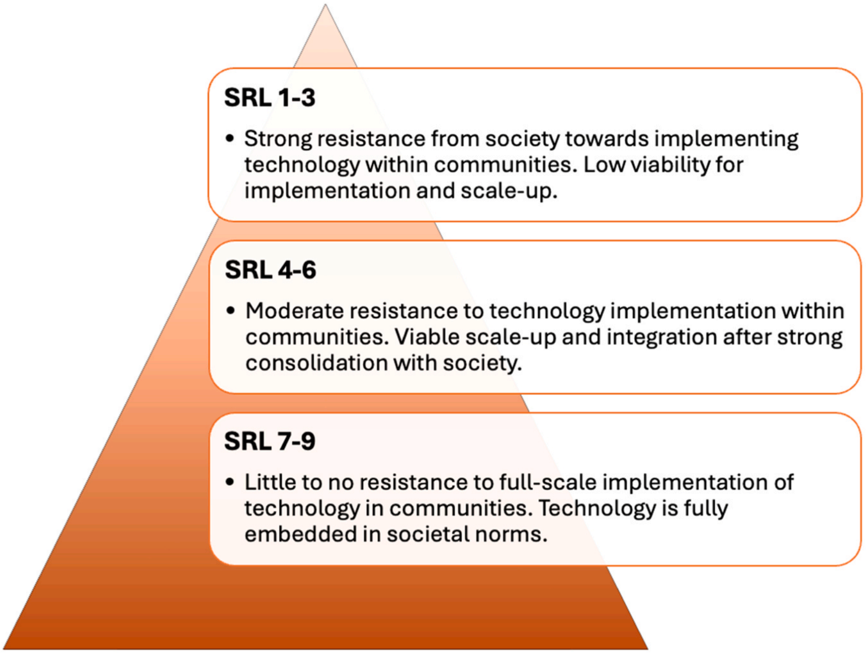
3.4. Societal readiness level

Public perception and societal acceptance play a critical role in commercialising hydrothermal technologies. The societal readiness level (SRL) is a helpful tool developed by the Danish Innovation Fund (DIF) [133] that evaluates the level of societal adaptation of a particular project, technology, product, process, intervention, or innovation with the intention to be implemented into society. The scale ranges from SRL1 to SRL9 and often depends on ethical, legal, social, and economic factors as demonstrated in Fig. 7 [133].

Assessing the societal acceptance of waste management technologies is crucial as it reflects how well society is prepared to accept and integrate that technology into its community, ensuring that the implementation is technically sound, socially viable, and ethical. While the technology's TRL assesses its commercialisation potential, an SRL assessment bridges the gap between technology and society, considering the broader societal context and identifying the potential challenges that might arise from introducing new technology into society. Table 6 highlights the estimated SRL levels of commonly implemented plastic waste treatment technologies such as landfilling, incineration, pyrolysis, conventional gasification, and mechanical recycling.

Hydrothermal technologies for plastic waste management are regarded as having an overall moderate SRL of around 5–6, depending on the hydrothermal technology, primarily due to limited public awareness and insufficient data on their environmental and economic benefits [18,134]. As HTL and HTC are more commonly adopted HTP technologies, they can be estimated to have an SRL of 6. On the contrary, with lower research numbers surrounding HTG and HTD, they struggle with broader public awareness and thus can be estimated to have an SRL of 5. When compared to conventional plastic waste management technologies in Table 7, HTP seems to rank relatively low on the SRL scale. The lack of knowledge about hydrothermal systems can lead to scepticism or resistance, particularly in communities where these facilities might be implemented, severely impacting the further development of hydrothermal plants [135]. Addressing these concerns through transparent communication with the public and industry stakeholders, community engagement, and educational initiatives is essential for building public trust and demonstrating the long-term benefits of hydrothermal technologies. Additionally, integrating these technologies into existing waste management frameworks through policy incentives and regulatory support can enhance their acceptance, paving the way for broader societal integration and commercial success.

Additionally, HTP operates under extreme conditions of high temperature and pressure, which raises specific public safety concerns. These include potential risks such as equipment failure, leaks, or explosions. Additionally, while HTP shows promise in laboratory settings, scaling up the technology for industrial applications presents numerous technical and economic challenges, such as accurate modelling of the systems and high operational and capital costs. Communities may be wary of supporting technologies that are not yet proven on a large scale due to uncertainties around operational reliability, cost-effectiveness, and environmental concerns around by-products or emissions [135]. To address these concerns, developers are encouraged to implement robust safety measures, conduct thorough risk assessments, and transparently communicate challenges and safeguards to the public. Additionally, adhering to both environmental and operational regulations is crucial for ensuring environmental, community, and worker safety. These include conforming to local trading waste discharge limits, ensuring emissions meet established environmental standards, and adhering to operational safety protocols relevant to high-hazard and high-pressure equipment. Ensuring regulatory compliance from the early stages of HTP integration not only addresses the potential environmental and occupational hazards but also strengthens the credibility and public acceptance of the technology.



SRL 1-3

- Strong resistance from society towards implementing technology within communities. Low viability for implementation and scale-up.

SRL 4-6

- Moderate resistance to technology implementation within communities. Viable scale-up and integration after strong consolidation with society.

SRL 7-9

- Little to no resistance to full-scale implementation of technology in communities. Technology is fully embedded in societal norms.

Fig. 7. Societal readiness level scale with relation to integration of waste management technologies within communities.

3.5. *Economic analysis*

3.5.1. *Economic potential of HTP technologies*

Hydrothermal processing offers significant economic potential through its ability to effectively process synthetic polymers and recover high-value products from plastic waste. This makes hydrothermal technologies attractive for various industries, particularly in increasing demand for sustainable plastic waste management and resource recovery. For instance, acetic acid, a by-product of HTD, commands a market price reaching up to US$750/tonne, with other high-purity organic acids commanding even higher prices depending on their application [136,137]. The global acetic acid market is driven by rising demand in industries like paints, coatings, adhesives, textiles, and food & beverage. However, market acceptance for HTD-derived acetic acids often hinges on achieving high purity standards and compliance with food-grade or pharmaceutical regulations, depending on the intended application. Similarly, HTC produces hydrochar, with an estimated minimum selling price of US$91/tonne, making it competitive with traditional coal products as a solid fuel alternative [138]. Market uptake is closely related to regional policies on carbon emissions, renewable energy mandates, hydrochars' calorific value, and contamination profile.

On the other hand, HTL generates bio-oil with prices ranging from US$0.75 to $1.41/L, approaching parity with fossil-derived fuels, which fluctuate between US$0.80 and $1.50/L in global markets [139]. Recent trends and interest in biofuels have spurred investment and research in refining HTL bio-oil to meet specific regulations and specifications of standard petroleum-based fuels. Furthermore, hydrogen gas extracted from the HTG process can achieve values up to US$1.94/kg, depending on purity and market conditions [140].

While price comparison offers a preliminary view of economic viability, market adoption of HTP-derived products depends on several factors beyond the cost, such as renewable energy mandates, carbon offset schemes, and waste management regulations. Certification standards for purity, safety, and performance, especially in sectors like food, pharmaceuticals, and energy, play a critical role in determining whether HTP-derived products can enter mainstream markets. For example, hydrochar derived via HTC must be compatible with existing combustion systems in power plants, which may require retrofitting or operational adjustments to accommodate differences in ash content, moisture levels, or combustion behaviour [141]. Similarly, bio-oils from HTL must meet stringent fuel standards to be accepted by refineries and end-users [142]. These technical and regulatory challenges can influence the pace and scale of market uptake regarding HTP-derived products.

3.5.2. *Challenges to commercial viability*

Despite these promising outputs of HTP technologies, their economic feasibility depends on several factors that hinder their application and widespread adoption. The cost of building and operating HTP systems is significant due to the need for specialised high-pressure and high-temperature reactors, contributing to substantial capital costs for these technologies. For instance, pilot-scale HTC systems have an estimated cost, ranging between US$700,000 and US$2 million, while larger commercial systems can range between US$5 million and over US$20 million, depending on capacity, automation, and integration with waste management infrastructure [138,143]. These costs vary with harsher conditions, where processes like HTL systems, which operate under higher temperatures and pressures, can range from US$20 million to over US$60 million on an industrial scale [144,145]. These costs exceed those of comparable pyrolysis and gasification units. A continuous pyrolysis reactor suitable for industrial use may cost between US$300,000 and US$1 million, while gasification reactors—such as fluidised bed systems—are typically priced at US$5000 to US$10,000 per kilowatt of installed capacity, translating to US$5 million to US$20 million for large-scale facilities which may be comparable to HTC systems depending on operation conditions or the need for additional treatments [146,147].

Additionally, maintenance costs pose a significant concern, as maintaining the high-temperature and high-pressure conditions essential for HTP processes requires considerable energy demands [22]. Helmer Pedersen and Conti [100] also outline how the reclaimed materials from the hydrothermal processing of plastics often require refinement to meet industrial standards, impacting overall profitability and increasing operating costs relating to hydrothermal technologies due to the required additional processing.

Additionally, using catalysts or chemical additives and optimising reaction parameters enhances the reaction efficiency for a high product recovery but significantly contributes to the recurring operational expenses [54,148]. Many catalysts, especially those based on noble metals like platinum, ruthenium, or palladium, are expensive, making their large-scale use costly. Similarly, catalysts often require regeneration due to deactivation, and in some cases, replacement is necessary if the regeneration process is ineffective, further adding to the operational costs of the process. To address this challenge, several articles explore the performance of alternative low-cost catalysts such as transition metal oxides and mixed metal sulphates. For instance, Bhaskar et al. [149] explore the use of copper oxide (CuO) catalysts for the improvement of HTD reaction, underlining that transition metal oxides are seen to increase the rate of the hydrothermal reaction and reduce the severity of the reaction. Additional research supports these results in the context of other HTP technologies, such as HTG and HTL, highlighting transition metal oxides as promising low-cost catalytic alternatives [150,151].

3.5.3. *Strategies to improve economic feasibility*

Ultimately, innovations and research development in reactor design are essential to mitigate these economic concerns surrounding the commercialisation of hydrothermal technologies for treating plastics. This helps implement effective energy recovery systems, decrease water usage, and optimise parameters to lower costs associated with operation. Additionally, various financial mechanisms, including subsidies, carbon credits, and government incentives, can significantly enhance the economic feasibility of HTP systems. Government subsidies can lower initial investment barriers by covering a portion of capital costs and funding research and development to improve efficiency. For example, research indicates that state-run hydrothermal processing operations have a 55 % probability of achieving a positive Net Present Value (NPV), compared to only 18 % for private-sector operations, primarily due to government support in infrastructure and subsidies [138]. Similarly, carbon credits provide an additional revenue stream by monetising emissions reductions, as HTP has been shown to produce lower greenhouse gas emissions compared to traditional waste management methods [152,153]. With the integration of these strategies, HTP has the potential to become an economically viable and environmentally sustainable solution to plastic waste management, paving the way for broader adoption and commercialisation of these innovative solutions.

4. Recommendation for future research

To further advance HTP of plastics, future research should focus largely on process optimisation through integrated systems, such as combining liquefaction and gasification, which warrants comparative studies that assess product yield, energy efficiency, and operational flexibility. Given the heterogeneity of real-world plastic waste, targeted investigations into feedstock composition, particularly additives and multilayer structures, alongside preprocessing strategies, could enhance degradation consistency while minimising energy input. Improvements in reactor design and materials science, especially in relation to corrosion resistance and thermal transfer under extreme conditions, are critical for scalable implementation. Additionally, research into techno-economic assessments, further public perception investigations, and policy frameworks may prove essential in understanding the real-world implementation of HTP technologies for plastics waste treatment.

5. Conclusion

With plastic waste posing as one of the major global environmental issues, hydrothermal technologies demonstrate considerable potential in waste reduction, hazard removal, and resource recovery, distinguishing themselves from traditional plastic waste treatment approaches. Hydrothermal processing (HTP) encompasses a variety of technologies, including hydrothermal carbonisation (HTC), hydrothermal liquefaction (HTL), hydrothermal gasification (HTG), and hydrothermal deconstruction (HTD), each producing distinct products with diverse applications across various industries. These by-products, including hydrochar, bio-oil, syngas, and organic acids, are pivotal in supporting the circular economy by providing renewable alternatives to fossil-based materials and fuels. Plastic degradation efficiency in HTP systems depends heavily on optimising temperature, reaction time, and catalyst presence. HTC and HTL are particularly effective for plastics with hydrolysable bonds, achieving product yields of up to 72 wt% hydrochar and 80 wt% bio-oil, respectively. Mixed waste streams can further enhance degradation performance and reduce energy demand. Conversely, HTD and HTG showed dependency on optimising operating conditions such as temperature and pressure, achieving high plastic degradation efficiencies of up to 95 % and 98 %, respectively, for most plastic types under optimal conditions. Despite their potential, HTP technologies face several barriers to scale-up, including high capital and operational costs, lack of standardisation, inconsistent experimental data, and reactor durability concerns, limiting the technology's accessibility, particularly for developing economies. This barrier can be reduced through further research and development, government involvement, and incentives. However, when compared with conventional plastic waste treatment methods, HTP demonstrates superior environmental performance through high-value recovery, low-to-moderate emissions, and minimal residual waste generation. For widespread implementation, public engagement and policy support are crucial, alongside further research and development to improve system reliability and cost-efficiency. Overcoming these challenges could position HTP as a pivotal strategy in addressing plastic waste sustainably, supporting a circular economy and contributing to a cleaner, healthier future.

CRediT authorship contribution statement

Saeid Baroutian: Writing – review & editing, Supervision, Conceptualization. **Céline Vaneeckhaute:** Writing – review & editing, Supervision. **Milica Mihajlovic:** Writing – original draft, Investigation, Formal analysis, Data curation. **Kaveh Shahbaz:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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