Report

Innovative technologies for treatment of mixed and sorted waste fractions

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SUMMARY

The amount of municipal solid waste generated is steadily increasing, while natural resources are depleted more and more. In this regard, efficient waste management and treatment are central to ensure that as many valuable resources as possible can be recovered at best possible quality. This should be done sustainably, with minimal energy needs and minimal harm to environment and society. On the other hand, economic viability is important to ensure commercial applicability. Numerous technologies have been developed or are under development, based on (hydro)thermal, chemical, mechanical, and biological approaches. As a consequence, there is an increasing variety of material fractions that can be recovered and enter the loop again – which, in turn, may stimulate new industrial activities.

This report provides an overview of selected innovative waste treatment technologies with long-term potential, focusing on approaches to manage plastic, food, wood, and textile waste. The exploration contributes to a greater understanding of the diverse array of solutions available for waste management and resource recovery, strengthening the knowledge base on sustainable waste management.

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List of abbreviations

AD   Anaerobic digestion
CCA   Chromated copper arsenate
CLC   Chemical looping combustion
CDW   Construction and demolition waste
F2F   Fiber to fiber
GHG   Greenhouse gas
HTC   Hydrothermal carbonization
HTL   Hydrothermal liquefaction
LCA   Lifecycle assessment
LHV   Lower heating value
MSW   Municipal solid waste
PET   Polyethylene terephtalate
PVC   Polyvinyl chloride
RDF   Refuse-derived fuel
SRF   Solid recovered fuel
UV   Ultraviolet
WtE   Waste to energy

1 Introduction

Globally, the amount of municipal solid waste generated is steadily increasing although there are local variations to the trend. Recent projections estimate a surge of global municipal solid waste (MSW) production by about 70 percent, to reach 3.4 billion metric tons by 2050[1]. At the same time, natural resources are depleted at an ever-increasing pace. The urgency to turn this development around grows from day to day.

The most effective approach is to avoid generation of MSW at all, through responsible production and usage of products and resources. In addition, the waste that actually has been generated should be managed in the best possible way, efficiently recovering as many resources as possible with minimal material degradation. In this way, resources can re-enter the manufacturing/usage loop again at highest possible level. These principles are conceptualised by the 10R framework of circular economy, see Figure 1.
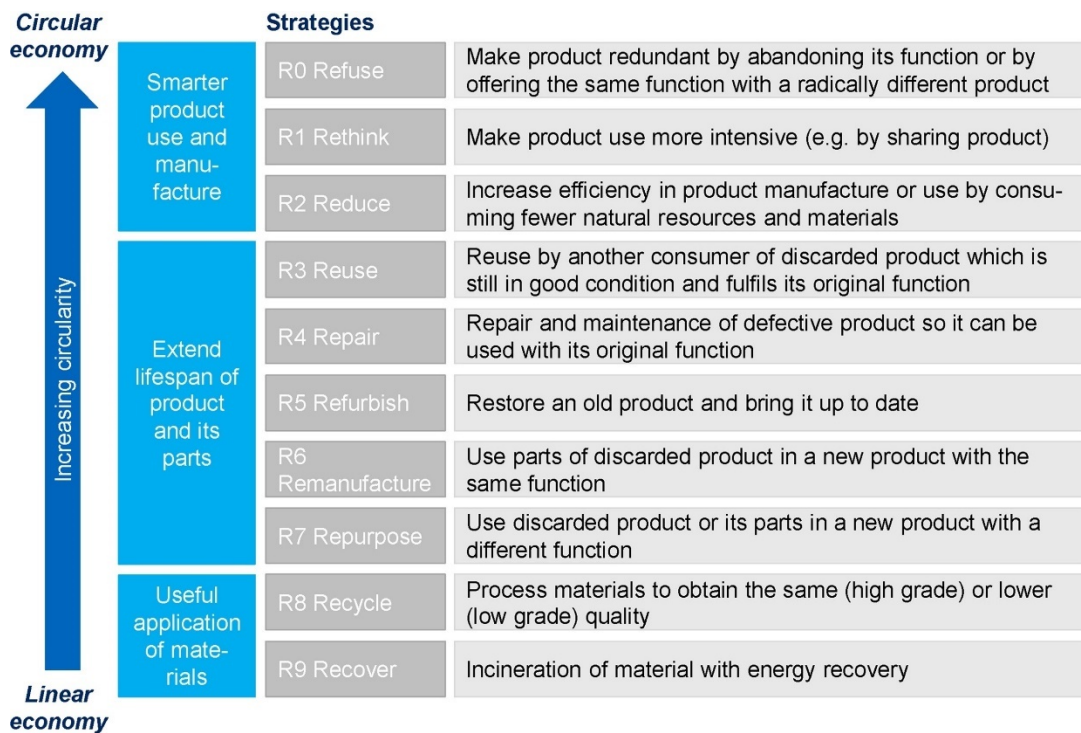

Circular economy	Strategies	
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

Figure 1. The 10R framework of circularity strategies [2]

In this context, the waste management and treatment sector takes a central role, from collection of waste and discarded products via sorting and resource recovery to making the recovered materials and resources available to enter the loop again. Demand for efficient and sustainable technologies for waste treatment is increasing, and R&D activities have intensified during the recent decades. A wealth of innovative approaches is developed and tested at different stages of maturity and technological readiness – which, in turn, also increases the variety of material fractions that can be recovered and used again in manufacturing. Sustainability of a technology means also that the benefits of increased resource recovery at higher levels should not be overshadowed by downsides such as energy usage or toxic residues. Economic viability is also an important aspect in the scaling up of promising approaches to industrial level and commercial implementation. For example, Garcia-Gutierrez et al. [3] state three criteria to select suitable treatment technologies for plastic waste: maximal material recovery with minimal processing impacts (especially with respect to energy), technical feasibility, and economic feasibility. In addition, potential commercial implementation of promising approaches may face challenges such as policy or regulatory issues, efficient integration with existing infrastructure, or organisational and structural aspects in the sector.
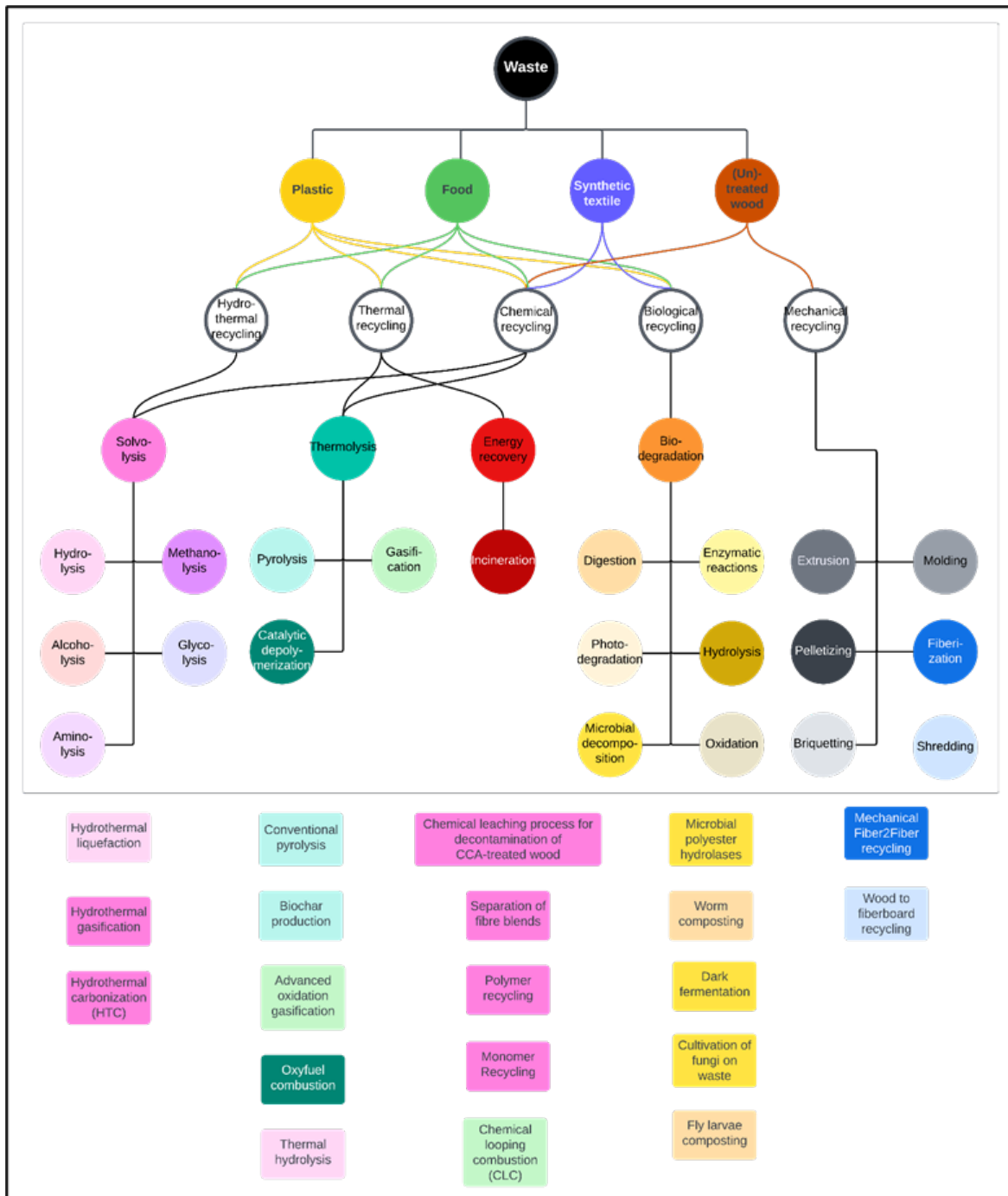
***Figure 2.** Categorization of waste treatment technologies per process type and waste fraction*

Technologies for waste treatment can be categorized according to the type of the underlying process and the treated waste fractions, see Figure 2. The *hydrothermal* category comprises technologies subjecting the feedstock to a combination of water and heat. The *thermal* category covers processes applying heat to facilitate various transformations and treatments. Treatments in the *chemical* category involve the use of chemicals such as solvents or acids to modify waste materials. The *biological* category is concerned with biodegradation of organic materials, emphasizing natural biological processes. Microorganisms such as bacteria and fungi are crucial to break down organic matter and to convert it to simpler forms. Lastly, the *mechanical* category includes treatments such as sorting, shredding and grinding that play a vital role in preparing waste materials for further processing or separation.

This report discusses selected waste treatment technologies with currently low technology-readiness level but promising long-term potential, contributing to a stronger knowledge base on sustainable waste management. It is a result of summer project work at the group for Operations Research and Economics at SINTEF Industry, in collaboration with researchers at the Department of Thermal energy at SINTEF Energy Research AS. The work was carried out in the context of the project "Waste-to-Energy and Municipal Solid Waste management systems in Circular Economy" (CircWtE), funded by the Research Council of Norway (project number 319795) under the SIRKULÆRØKONOMI program. Project partners are CIVAC, Franzefoss Gjenvinning, NOAH, NTNU, Oslo REG, SINTEF Industry, Tafjord Kraftvarme, and Trøndelag county council, managed and lead by SINTEF Energy Research AS. The scope of the CircWtE project is to develop knowledge-based tools and methods to explore how future MSW management systems may look like in a circular economy. Specifically, this report contributes to work package SP2 investigating current and future waste treatment technologies and their role in a (circular) MSW system.

Table 1 gives an overview of the technologies explored in detail, distinguished according to four main waste fractions: food, plastic, wood, and textiles. These fractions were selected due to their anticipated growth or currently inadequate management practices in Norway – at the same time most of them are targeted by new regulation (material recovery targets, waste reduction strategies, separate collection). For each fraction, several technologies were selected to provide a representative mix of different process types. Further technologies are mentioned in the Appendix, underscoring their importance, but also a need for further investigation. For example, biological processes seem not as explored as mechanical, chemical or hydrothermal technologies, although, e.g., dark fermentation, fly larvae composting, and cultivation of fungi on waste appear promising. Hydrothermal gasification and oxyfuel combustion also show a high application potential.

Table 1. Waste treatment technologies discussed in this report with main waste fractions addressed

Technology name	Process type	Food waste	Plastic waste	Textile	Impregnated wood	Industrial wood
Thermal hydrolysis	Thermal	X				
Hydrothermal carbonization	Hydrothermal	X				X
Chemical looping combustion	Chemical	X	X			
Conventional pyrolysis	Thermal	X	X			
Hydrothermal liquefaction	Hydrothermal	X	X			X
Advanced oxidation gasification	Thermal		X			
Biochar production	Thermal	X				
Chemical leaching to decontaminate CCA-treated wood	Chemical				X	
Wood to fiberboard recycling	Mechanical					X
Fiber2Fiber recycling	Chemical			X		
Monomer Recycling	Chemical			X		
Polymer recycling	Chemical			X		
Separation of fibre blends	Chemical			X		
Microbial polyester hydrolases	Biological		X	X		

The remainder of this report describes the selected technologies, discussing conceivable applications and shedding light on benefits, challenges, and long-term implementation potential. **Section 2** is concerned with processes to treat food waste, while **Section 3** addresses approaches for plastic waste. Processes to treat wood waste, especially from construction and demolition, are discussed in **Section 4**, while **Section 5** focuses on used textiles and textile waste. **Section 6** draws conclusions. Further promising technologies are listed in the **Appendix**.

2 Food waste

2.1 Thermal hydrolysis

2.1.1 Technology description

Thermal hydrolysis is a pre-treatment process technology currently applied in wastewater treatment plants that use anaerobic digestion (AD) of sewage sludge and food waste/biomass. The main output resources of the digestion process are biosolids and biogas. The biosolids can be used directly as fertilizer due to their high nutrient concentration or further processed into concentrated fertilizer pellets.[4] Alternatively, the digestate is incinerated. The biogas can be used for heat or electricity generation or upgraded into biofuel, which makes this "by-product" a valuable good. Note that AD of food waste is considered recycling only if the digestate/biosolids are utilized as a fertilizer.

Thermal hydrolysis breaks down the organic structures of the sewage sludge or biomass feedstock to improve their availability in the subsequent digestion process, increasing the biogas yield. In the first step of the pre-treatment, the feedstocks are either mixed and dewatered or dewatered separately to 16-18% dry solids concentration. In the next step, the dewatered sludge/biomass is fed into the pulper to be homogenized and pre-heated using steam. The warm sludge is fed into a reactor, where more steam is added to raise the temperature to 160-180°C at a pressure of about 6-9 bars for 20-30 minutes. Then, the hydrolysed sludge is passed to a flash tank at atmospheric pressure. The sudden pressure drop leads to substantial cell destruction of the organic structures, making them available for the anaerobic digestion process. The steam generated by the pressure release in the flash tank is returned to the pulper, thus reducing overall energy demand. The sludge leaving the flash tank is cooled in heat exchangers to the typical temperature for anaerobic digestion and then fed into anaerobic digesters for the conventional biogas production process.[4]

2.1.2 Technological development stage

Thermal hydrolysis as pre-treatment process for sewage sludge is currently practiced on industrial level by multiple enterprises in Norway. The processing of biomass in addition to sewage sludge seems to be less practiced. This could be due to a lack of well-established guidelines, standards, and proven long-term performance data. Another explanation might be that, while the enhanced biodegradability of sewage sludge after thermal hydrolysis is well-documented, the extent to which this applies to other types of biomass has not been thoroughly investigated yet such that potential benefits may not be as clear.

An example of a waste treatment plant using thermal hydrolysis is IVAR IKS in Stavanger-Grødaland, with a solution provided by Cambi.[5] The plant has separate pre-treatment systems for food waste from households and grocery stores and for wastewater sludge, septic sludge and industrial organic wastes.[4] Another provider of thermal hydrolysis solutions is TerraNova Energy, which currently only deploys plants with sewage sludge as feedstock. An attribute setting TerraNova apart from its competitors is the absence of steam as heat transfer medium in the process. This allows to reduce overall energy demand.[6]

2.1.3 Advantages compared to conventional biogas production

Thermal hydrolysis as a pre-treatment for anaerobic digestion can lead to increased biogas production, potentially up to 50%. This results from the improved breakdown of organic materials during anaerobic digestion due to the prior partial organic structure breakdown as part of the pre-treatment.[4] The process can lead to a reduced volume of biosolids due to both increased conversion of organic matter into biogas and increased dewatering efficiency at the end of the digestion process.

Furthermore, the quality of biosolids produced through anaerobic digestion is improved. They are less odorous and contain fewer pathogens, making them more suitable for use as soil amendment or fertilizer. In addition, waste treatment staff can handle such pre-treated biosolids better than non-pre-treated ones, leading to improved health, safety and environment conditions.[4]

The pre-treatment also accelerates the hydrolysis step in anaerobic digestion. Increased availability of the organic compounds for conversion into biogas allows for better capacity utilization and increases throughput without the need for extensive expansion or larger digestion facilities.

Lastly, thermal hydrolysis as a pre-treatment step diminishes the carbon footprint of AD. The improved dewatering efficiency reduces energy consumption. Additionally, as the lower volume of biosolids produced reduces transportation needs, associated carbon emissions are reduced as well.

2.1.4 Current challenges to be overcome before commercialization of technology

Currently, the direct use of biosolids as fertilizer is heavily regulated by the Norwegian Ministry of Agriculture and Food. Biosolids from sewage sludge cannot be spread on land where vegetables, potatoes, berries or fruit are grown.[7] If they are to be used in ecologic farming, an exemption by the food safety authority is required.[8] This regulation is under revision and might be subject to change in the future. If the biosolids are processed further into fertilizer, other regulations apply, mainly concerning recording of the fertilizer usage.[7] All present industrial applications in Norway of thermal hydrolysis as pre-treatment for anaerobic digestion use a combination of sewage sludge and biomass. Hence, the regulations on the resulting biosolids decrease the market value of the technology.[4]

Thermal hydrolysis processes require significant energy inputs due to the need for elevated temperatures and pressures. This can contribute to higher operational costs and environmental impacts, especially if fossil fuels are used for heat generation.

During thermal hydrolysis, certain compounds may form that can interfere with the activity of anaerobic microorganisms in the subsequent anaerobic digestion process, reducing their ability to efficiently break down organic matter. This can result in lower biogas production and decreased process efficiency. Also, dark-coloured recalcitrant compounds may form in the treated sludge. These compounds are resistant to degradation and can negatively impact the post-dewatering anaerobic digestion process. They absorb ultra-violet (UV) light that, consequently, may not penetrate the cells of microorganisms adequately, leading to less efficient inactivation of pathogens and compromised disinfection.[9]

Advanced thermal hydrolysis may outweigh some of these challenges. Such processes incorporate Fenton's peroxidation, which involves the use of hydrogen peroxide (H_2O_2) with or without a catalyst. This enhances the breakdown of organic matter by promoting oxidation reactions. The approach focuses on minimizing the formation of refractory materials during thermal hydrolysis, leading to more complete degradation of organic matter. Optimized process conditions promote the activity of methane-producing microorganism. This improves the efficiency of subsequent anaerobic digestion and results in higher biogas yields. Advanced thermal hydrolysis techniques operate at lower temperatures and pressures and with shorter treatment times. This contributes not only to improved safety, but also to lower energy consumption and associated costs. However, it should be noted that the use of high concentrations of H_2O_2 can have drawbacks. Excessive levels can inhibit the subsequent anaerobic digestion and reduce methane production. Therefore, careful optimization and control of the H_2O_2 dosage are necessary to ensure its effectiveness as an oxidation agent without negatively impacting the overall anaerobic digestion process.[9]

2.1.5 Further development

As mentioned, thermal hydrolysis pre-treatment has potential for further improving process parameters and exploring new approaches to increase its effectiveness for biomass pre-treatment for biogas production.

Apart from thermal hydrolysis, there are other biomass pre-treatment processes that show potential for enhancing biogas production. These processes are currently under research and industrial development, but their details are not further explained in this report. One such process is *alkaline pre-treatment*, suitable primarily for organic compounds and lignocellulosic materials. It involves the use of alkaline substances to break down the complex organic structure and to facilitate subsequent anaerobic digestion. *Ultrasonic pre-treatment* can be applied to a wide range of biomass feedstocks. Ultrasonic waves are used to create

cavitation and to disrupt the structure of biomass, increasing its accessibility to microorganisms during AD. Application of *enzymes* is also explored as pre-treatment for various biomass feedstocks. Enzymes can break down complex organic compounds and make them more easily digestible for microorganisms. However, the use of enzymes can be costly, which presents a challenge for large-scale applications. *Electroporation* is mainly suitable for organic compounds. It involves the application of electric pulses to disrupt the cell membranes of biomass, improving the release of organic matter and facilitating subsequent AD.

2.2 Hydrothermal carbonization

2.2.1 Technology description

Hydrothermal carbonization (HTC) is a thermochemical process that enables the conversion of wet biomass feedstocks, such as sewage sludge, aquatic biomass, agricultural residues, and industrial and animal wastes, into hydrochar. It involves a series of reactions including hydrolysis, dehydration, decarboxylation, and aromatization. Operating within a temperature range of 180 to 250°C and under autogenous pressure, HTC typically requires a residence time for the feedstock from 0.5 to 8 hours [10].

The HTC process commences with reducing the moisture content of the wet biomass feedstock to 5-30% dry matter. Food waste has generally already a dry matter around 30%, and a necessary pretreatment would be shredding. Then, the biomass is preheated in an input heat exchanger. Carbonization of the biomass is done in a stirred reactor at around 200°C for approximately 5 hours, potentially under addition of catalysts. After the carbonization step, the resulting carbon slurry is cooled using output heat exchangers and then dewatered until it reaches a dry-matter content of 65-70%, enabling its separation from the press [6].

An optional step involves further drying of the carbon in a low-temperature drying unit to enhance its hydrophobic characteristics, resulting in a solid product with similarities to lignite.[6] This modified form of carbon can be easily pelletized, facilitating convenient handling and utilization.[11] Another possibility is the utilization of dewatered HTC filtrate in subsequent treatment stages to recover valuable resources such as phosphorus, nitrogen and biogas from the by-products of the HTC process.[6]

The produced hydrochar has various applications. Its energy content depends on the feedstock used in the process. Generally, hydrochar has a calorific value ranging from 15 to 30 MJ/kg, which can exceed the calorific values of typical raw HTC feedstocks (13 to 19 MJ/kg) but is lower than that of bituminous coal (30 to 35 MJ/kg). Still, certain hydrochar types possess sufficient energy content to be a viable option for solid fuel. Additionally, the char can be a valuable feedstock for producing liquid fuels, including bio-oil and blend-stock fuels, as well as gaseous fuels like syngas. Hydrochar can be used to improve soil fertility and structure. Its porous nature makes it an effective absorbent in water and wastewater treatment once chemically activated, and it also holds potential for carbon sequestration, aiding in the mitigation of greenhouse gas (GHG) emissions.[10] The latter aspect is further discussed in the context of biochar (section 3.1.4). In addition, HTC yields products such as aqueous sugars, acids, carbon dioxide, and water.[11]

2.2.2 Technological development stage

While HTC shows promise in converting organic waste materials into hydrochar, its commercial implementation on a large scale is still limited.[10] However, there are companies that have taken steps towards large-scale hydrochar production. One example is TerraNova Energy [6], which has established an operational plant called TerraNova®ultra in Mexico City. This plant utilizes HTC technology to convert organic waste materials into biocoal. The produced biocoal is then fed into a coal-fired power plant, contributing to the generation of electricity. To obtain coal pellets as process output, the carbonized biomass undergoes drying in a low-temperature drying unit. This unit is powered by a pyrolysis plant operating on woody and plastic waste. Utilizing waste materials as a fuel source, the process aims to enhance sustainability and minimize the environmental impact.[6]

2.2.3 Advantages compared to incineration and biochar production

HTC facilitates enhanced nutrient recovery. The process generates hydrochar and process water retaining essential nutrients, including phosphorus, potassium, and nitrogen, which promote plant growth. These nutrients would be lost during biomass incineration. On the other hand, depending on the feedstock used, the resulting products may contain metals like Ni, Pb, Cd, and Cr, which are unwished for.[10]

The technology allows to process feedstocks with varying moisture content, eliminating the need to pre-dry the biomass. This not only saves energy, but also reduces costs – setting HTC apart from other methods that mandate dry feedstocks, such as biochar production (section 3.1.2).[10]

Hydrochar produced through HTC has a high dewatering efficiency, rendering it well-suited for effective biosolids management. This is attributed to the hydrochar's ability to facilitate the release of bound water within the managed flow.[10]

Compared to conventional methods like composting, HTC has advantages such as enhanced energy recovery and reduced emissions of pollutants and odours.[10] Potential contamination by (micro) plastic is a main issue for further treatment of food waste – HTC eliminates challenges related to plastic and other impurities in the feedstock that end up in the digestate and reduce its useability as fertilizer.

2.2.4 Current challenges to be overcome before commercialization of technology

Successful large-scale deployment of HTC is currently hindered by several uncertainties, primarily revolving around understanding how heat is transferred within the system and which products can be obtained, and ensuring economic viability. To address these concerns, studies should be conducted that focus on utilizing different types of feedstocks in reactors of significant capacity.[10]

HTC involves heating the biomass to initiate carbonization, which demands a considerable amount of energy. Additional energy might be needed to dry the material after carbonization. This high energy consumption represents a challenge that needs to be addressed to enhance efficiency and sustainability.[10]

By-products such as water and gas are currently not fully utilized or adequately managed. For instance, the process water could be recycled and reintroduced into the HTC system, reducing water consumption and potentially increasing process efficiency. Alternatively, it could be used for anaerobic digestion, a process that converts organic waste into biogas, thus generating additional energy. Failure to harness the potential of these by-products represents a missed opportunity and results in avoidable waste generation.[10]

2.2.5 Further development

To address the uncertainties mentioned above and to maximize commercial viability of HTC, robust pilot-scale systems should be established that can handle diverse feedstocks and different processing conditions. Design of such systems should be coupled with rigorous analyses of product quality to assess the economics of large-scale commercial implementations.[10]

Hydrochar production can be integrated with existing energy infrastructure, such as coal-fired power plants. This offers several benefits, including enhanced resource utilization and reduced reliance on traditional fossil fuels, improving overall efficiency and sustainability.

Furthermore, HTC holds exciting prospects to include plastic feedstocks, but thorough investigations of technical feasibility are necessary. Additionally, concerns related to the potential toxicity of the residues resulting from plastic feedstocks must be addressed to ensure the safety and viability of the process. By overcoming these challenges, HTC can further diversify its potential and contribute to a more sustainable and efficient waste management framework.[10]

2.3 Chemical looping combustion

2.3.1 Technology description

Chemical Looping Combustion (CLC) is an emerging technology designed to capture carbon dioxide (CO_2) in post-combustion processes, particularly in coal-fired power plants. It has gained recognition for its ability to capture CO_2 with minimal energy penalties and cost.[12]

Feedstock for the CLC process are solid recovered fuel (SRF) and refuse-derived fuel (RDF), which are currently used in the conversion of biomass through fluidized bed combustion (FBC) in Waste-to-Energy (WtE) plants. In general, the lack of standardization and varying calorific value of RDFs may pose risks to the process while SDFs is a more standardized fuel that must comply with regulations.[12]

The CLC system comprises two fluidized bed reactors, an air reactor and a fuel reactor, with a solid oxygen carrier, typically a metal oxide, circulating in between. The air reactor facilitates the oxidation of the oxygen carrier using atmospheric oxygen. In the fuel reactor, a series of steps take place, including drying, devolatilization, and gasification of SRF. The generated gases, such as carbon monoxide (CO), hydrogen(H_2), and methane (CH_4), react with the oxygen carrier to produce carbon dioxide (CO_2) and water (H_2O). The reduced oxygen carrier particles are then transported back to the air reactor for a new round of oxidation. Unconverted char particles are burned with air in the air reactor, resulting in the emission of CO_2. To prevent direct emissions, non-converted gases (CO, H_2, CH_4, nitrogen (N_2)) exiting the fuel reactor can be subjected to a post-oxidation process resulting in more carbon dioxide and water.

The flue gas produced in the fuel reactor mostly consists of CO_2 and water vapor, that can be easily condensed. Thus, the CO_2 requires minimal purification in comparison to conventional combustion, significantly reducing the energy costs of capture. The captured CO_2 is then compressed and transported to designated sites for permanent storage (e.g., former gas fields, saline aquifers). Alternatively, it has applications in chemical synthesis, such as the production of methanol or synthetic natural gas. This process often involves combining CO_2 with hydrogen obtained through the electrolysis of water.

In addition to CO_2 capture, CLC generates highly valuable by-products in the form of heat and steam that can be utilized for various purposes, including power generation, heating, and industrial processes. Finally, solid residues are produced, including ash and unconverted char particles, that require proper management and disposal methods to ensure environmental safety.

2.3.2 Technological development stage

CLC technology has undergone testing in multiple pilot plants utilizing various types of solid fuels although most tests have so far focused on coal. Typically, two coupled fluidized bed reactors are employed with fuel inputs reaching around 1 MW_{th}. The feasibility of CLC for solid waste management has been substantiated by various studies and laboratory trials. For instance, the Laboratory for Chemical Technology at Ghent University tested CLC using corn stalk, rice straw, and palm oil mill effluent streams as feedstocks. The Technical University of Darmstadt conducted tests with a combination of coal and torrefied biomass. Chalmers University performed tests using biochar and crushed wood pellets, while Spanish research investigated CLC with forest and agricultural residues. Ongoing trials study CLC as a means to capture CO_2 from plastic waste and, thus, as a potential solution to manage plastic waste and reduce CO_2 emissions.[12]

2.3.3 Advantages compared to conventional oxy-combustion capture schemes

The potential for low CO_2 capture costs in CLC is based on the technology's high efficiency. The inherent ability to separate CO_2 from the flue gas eliminates the need for energy-intensive gas separation processes required in conventional oxy-combustion capture schemes, thus reducing energy requirements significantly. CLC offers the advantage of using oxygen carrier materials, such as natural ores and waste materials, that tend to be more cost-effective compared to amine solvents used in amine scrubbing and sorbents used in carbonate looping for carbon capture. For the post-oxidation chamber, CLC requires typically only 10-20%

of the oxygen supply needed in other oxy-combustion capture schemes such as oxy-fuel combustion. This reduces costs and logistics associated with oxygen supply.[12]

CLC provides the unique capability of generating power, heat, and CO_2/chemicals simultaneously. This multifunctionality allows for direct subsequent utilization of captured CO_2 in the synthesis of valuable chemicals. Additionally, the heat from off-gases produced during the process can be effectively harnessed for power and/or heat generation, enhancing energy efficiency. This reduces total process costs, making it more economically viable and sustainable.[12]

A study by Mohn et al. in 2022 [13] assesses techno-economic performance of CLC in a 60 MW_{th} WtE plant utilizing SRF and indicates CO_2 avoidance costs of below 90 €/tonne. In comparison, the most mature option for CO_2 capture using amine scrubbing (MEA) has CO_2 avoidance costs of 288 €/tonne, while carbonate looping has costs of 119 €/tonne. Overall, it shows CLC as an attractive solution to reduce carbon emissions.

Finally, the technological similarity of CLC to solid-fuel combustion in conventional fluidized beds allows to leverage existing knowledge and process infrastructure, making it cost effective and feasible for implementation in various industries.[12]

2.3.4 Current challenges to be overcome before commercialization of technology

Trace elements and minor species present in the waste materials may lead to corrosion and fouling, requiring maintenance and cleaning procedures. CLC systems are also susceptible to the interaction of impurities in the input materials, such as alkali metals and chlorine, with the oxygen carrier material. This leads to agglomeration and fouling, which decrease system performance and operational reliability.

Inhomogeneous waste can lead to fluctuating gas composition, requiring additional control measures. The high volatile content of the used SRF or RDF necessitates thorough mixing of gas and oxygen carrier particles. Both effects are challenges to maintain stable combustion conditions and optimal carbon-capture efficiency. The potential incomplete conversion of gases to CO_2 and H_2O, can also result in lower efficiency.[12]

Implementing CLC for carbon capture typically requires a prior process to generate SRF or RDF in sufficiently stable quality, adding complexity and potential costs to the overall waste management and carbon capture infrastructure.[12]

2.3.5 Further development

Further research is important to identify optimal conditions for CLC that minimize emission levels and maximize combustion performance. Additionally, pilot-scale demonstrations of the process are necessary to validate the technology's feasibility and to assess its scalability for real-world implementation.[14]

3 Plastic waste

3.1 Conventional pyrolysis

Pyrolysis is a thermal process that converts a feedstock such as plastic, mixed or food waste into high-value products such as pyrolysis gases, oils, and char. The efficiency of the process, yield and composition of the resulting fuels are affected by feedstock composition, heating rate and pyrolysis temperature. [15] It should be noted that pyrolysis of plastic is considered recycling only if the resulting oil is used to produce new chemicals/plastic. When it is used for fuel production, the process is classified as energy recovery.

3.1.1 Technology description plastic or mixed waste feedstock

Plastic waste is converted by pyrolysis into combustible pyrolysis gas and liquid pyrolysis oil without oxygen, using a catalyst at temperatures ranging from 350-700 °C to facilitate polymer cracking. [16]

Alongside rotary kilns, fluidized bed, tubular and certain batch and semi-batch reactors, fixed-bed reactors (Figure 3) are most commonly used for pyrolysis of waste. The fixed-bed reactor is loaded with feedstocks and quartz sand through feed hoppers equipped with screw feeders. External heating of the reactor is achieved using natural gas or pyrolysis gas, while a continuous nitrogen gas flow maintains the necessary process conditions. After the pyrolysis reaction, the solid residues are discharged into a designated char hopper. Gases and vapours are extracted utilizing ceramic hot-gas filter elements, followed by a two-stage condensation unit. They are directed through a column containing catalyst pellets (typically, natural or modified zeolites as well as metal oxides and bimetallics), and the resulting products are collected using a water-cooled condenser.[17]
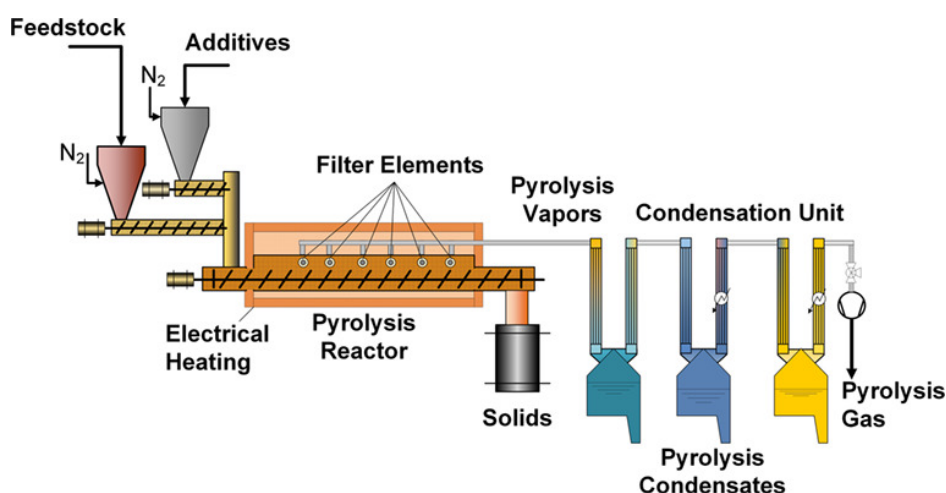

***Figure 3.** Fixed-bed reactor for pyrolysis with feed system, hot-gas filtration, solids hopper, and condensation stages for the pyrolysis vapours [17]*

Slow pyrolysis minimizes the production of by-products.[15] Higher temperatures yield more short-chain products, gases, and coke, while lower temperatures result in more waxes and oily components.[17] Optimal oil yields are obtained at processing temperatures between 500°C and 600°C.[16]

Pyrolysis oil from plastic waste contains significant amounts of gasoline and diesel fractions. However, yield and quality vary widely depending on the type of feedstock. Figure 4 gives an overview of fuels obtained from different types of plastics, such as high-calorific-value liquid oil from polyvinyl chloride (PVC) and aromatic hydrocarbons from polystyrene (PS). However, the wide carbon number distribution, low octane value of the gasoline, and high olefin content make pyrolysis oil unsuitable for direct use as fuel. Additional upgrading and refining processes are necessary to enhance quality and composition.[15] Once upgraded and

refined, the oil can be used for heat production, blended with conventional fuels for transportation [16], electricity generation, synthetic gas production, or chemical applications.

Type of plastics	Conditions	Products	Yield (%)	Refs.
PET	T=400/425/450°C	C_{10}-C_{14} kerosene	/	(Prurapark et al., 2020)
HDPE	T=575°C, Ratio of plastics to biomass=1:4	Liquid oil	57.6	(Xu et al., 2020)
PE/PP/PS (Mixture)	T=500°C, Heating rate =20°C/min	C_5-C_{19} liquid oil	50.9	(Singh et al., 2019a)
PS	T=500°C, Filling ratio of heat carrier=15%	C_5-C_{12} liquid oil	82.5	(Zhang et al., 2017)
PE	T=400°C	Liquid oil	92.0	(Sarker et al., 2012a)
LDPE/PP (Mixture)	T=275°C, Time =80min	C_5-C_{12} gasoline fraction	48.6	(Shah et al., 2010)
PP	T=550°C	Liquid oil	74.4	(Jin et al., 2018)
LDPE	T=500°C, Heating rate=6°C/min	Liquid oil	80.4	(FakhrHoseini and Dastanian, 2013)
PP	T=300°C	C_6-C_{16} naphtha	50.0	(Ahmad et al., 2014)
PP	T=450°C, Ratio of plastics to RH=1:1	C_6-C_{14} diesel	55.6	(Suriapparao et al., 2020)
PS	T=350°C, Time =40min	Liquid oil	88.0	(Bajad et al., 2017)
PE/PP/PS/PET/PVC (Mixture)	T=500°C, Time =30min	C_5-C_{16} liquid oil	87.0	(Lopez-Urionabarrenechea et al., 2015)

Figure 4. Fuel conversion from various plastic types via traditional pyrolysis [15]

Pyrolysis gas consists mainly of carbon monoxide (CO), methane (CH_4), hydrogen (H_2), carbon dioxide (CO_2), and nitrogen compounds. It has a calorific value of 10-15 MJ/Nm^3 (slow pyrolysis). The gas is commonly used as an energy source for the pyrolysis process itself. However, with unknown waste composition, unwanted compounds may be present. Therefore, emission control units and gas cleaning devices should be employed regardless of whether the gas is recycled back into the pyrolysis process.[16]

Pyrolytic char is also produced, which is a carbon-rich matrix containing inorganic compounds and by-products of the pyrolysis process. Despite pre-pyrolysis separation techniques, hazardous elements like heavy metals and S, Cl, and Ni can remain in the char, and proper characterization is important to evaluate its environmental and human impact. The char can be combusted for energy generation during the pyrolysis process or used in applications such as filler material for composites or hybrid fillers in the cement industry. There are also many activities concerning metallurgical applications of non-conventional char where pyrolytic char may play a role. Solid carbon fractions obtained at temperatures below 700°C contain

impurities and find application in low-cost uses like soil-quality enhancement, oil spillage adsorbents, and industrial cleaning agents.[16]

3.1.2 Technology description biochar production

Biochar production refers to the thermal degradation of *organic materials* into carbon-rich by-products at a moderate temperature (300–800 °C) and low pressure with little or no available oxygen. To obtain a more versatilely usable product, the feedstock is restricted to food waste.[18]

Food waste has a higher water content than plastic and mixed waste, and pre-treatment to dry the feedstock and to evaporate the water is needed, which is energy intensive and leads to high operating costs. Integrated conversion systems such as the combination of anaerobic digestion (AD) or HTC with pyrolysis are explored since the former processes reduce the water content of food waste and, in the case of AD, recover biogas and nutrients from the digestate. The remaining solid residue can then be pyrolyzed for the co-production of biochar and biofuels (e.g., syngas). While the quality of pyrolysis oil and biochar resulting from AD combined with pyrolysis is higher than from pyrolysis alone, the quality of the pyrolysis gas is lower.[18]

The biochar obtained from the pyrolysis can be used as solid fuel, adsorbent for environmental remediation (e.g., CO_2 capture), metallurgical applications, and electrochemical applications (e.g., energy storage and conversion). Moreover, it can be activated and/or modified to obtain high-performance engineered biochar for energy and environmental applications such as the treatment of contaminants.[18]

3.1.3 Technological development stage

Pyrolysis for waste treatment is a well-developed technology with commercial success in several countries worldwide, including Europe. Notable examples of pyrolysis implementations for *plastic and mixed waste* are Quantafuel [19] and Arcus [20, 21], energy companies based in Norway and Germany, respectively. Similarly, commercial-scale operations using *biowaste* have been implemented. For example, Ecoera [21], a Swedish company, Carbofex [22], a Finnish company, and the Australian company Rainbow Bee Eater [23] have established themselves in the biochar marked utilizing pyrolysis technology.

3.1.4 Advantages compared to conventional waste treatment technologies

Depending on the application of the output products, pyrolysis of plastic and food waste can help to mitigate GHG emissions. Diverting these waste materials away from traditional disposal methods like incineration, it reduces the release of methane, a potent GHG, and other harmful emissions. Utilization of the produced fuels or biochar as alternative energy sources can further reduce reliance on fossil fuels, thereby reducing overall carbon dioxide emissions and contributing to climate change mitigation efforts.

Pyrolysis of food waste generates biochar, a carbon-rich solid residue, which can be engineered to have functionalized properties. High adsorption capacity or catalytic activity of such engineered biochar help to remove pollutants or contaminants from various sources, including water or soil. This presents an environmentally sustainable approach to tackle emerging contaminant issues, contributing to better waste management and environmental remediation efforts.[18]

Another advantage specifically related to food waste is that the obtained pyrolytic gas surpasses biogas generated by AD in terms of quality, primarily due to its elevated lower heating value (LHV). Fuels with higher LHV can produce more heat per unit of fuel and are thus more efficient and effective as energy sources. Hence, such fuels contribute to efficient utilization of resources and mitigate environmental impact.[18]

3.1.5 Current challenges to be overcome before commercialization of technology

Optimal fuel conversion with minimal amounts of by-products requires high temperatures and long reaction times, resulting in substantial energy needs – which can limit the overall efficiency of the process.

Pyrolysis often yields low quantities of liquid oil, with a wide range of carbon numbers. To obtain a more standardized and usable product, additional refining processes are needed as post-treatment, adding to complexity and costs. [15] Co-pyrolysis of plastic waste with biomass is a potential approach to improve the

formation of desired products [15] but may impact the calorific value of the derived pyrolysis oil (about 15-20 MJ/kg for biomass-derived oil vs. 30-45 MJ/kg for plastic-derived oil [16]).

Generation of volatile compounds during pyrolysis can lead to reactor clogging, requiring maintenance and cleaning procedures. Addressing these issues can be expensive and time-consuming and impact economic viability of the pyrolysis process. Distillation and cracking can generate a substantial amount of residues, and their proper disposal can pose environmental and logistical challenges.

For *biochar production*, a significant challenge lies in the high moisture content of the feedstock. Developing a low-cost and efficient dewatering pre-treatment method is crucial to optimize the process. Without an effective solution, the energy consumption associated with dewatering can undermine overall sustainability and cost-effectiveness of biochar production.[18]

3.1.6 Further development
The outlook for pyrolysis as a waste treatment method is promising. With current commercial exploitation, advancements are expected to reduce its energy intensity and to incorporate feedback loops. Efforts focus on optimizing process parameters, developing efficient reactor designs, and exploring alternative energy sources. Feedback loops involve utilizing by-products of other processes, thus enhancing resource utilization and energy efficiency. Advancements in catalyst development and process optimization aim to improve product yields and reduce environmental emissions. Overall, pyrolysis holds potential for a sustainable waste management solution.[15]

3.2 Hydrothermal liquefaction

3.2.1 Technology description
Hydrothermal liquefaction (HTL) is a process that can convert plastic waste at lower temperatures than conventional pyrolysis. It involves temperature of about 250-400 °C and pressure in the presence of water to break down plastic polymers, producing fuels (gas, oil) and waxes. The effectiveness of HTL relies on hydrolysis, which can be performed under various conditions, enabling treatment of different plastic types. As for conventional hydrolysis, it is considered recycling only if the resulting oil is used for chemicals/plastic production.

When water is used in a *sub-critical* condition for HTL, the process parameters include low temperature, low pressure, and a short residence time for the plastic in the water. This is highly efficient for breaking down heteroatom-containing synthetic polymers like epoxy, polyamide 6 (PA6), polyamide 66 (PA66), polyethylene terephthalate (PET), polycarbonate (PC), and polyurethane (PUR).

In contrast, utilizing water in a *supercritical condition* requires higher process temperatures, increased pressure, and shorter residence time. This is most efficient for polyolefins such as polyethylene (PE), polypropylene (PP), and polystyrene (PS). However, supercritical HTL tends to be more expensive due to higher energy requirements, and the high-pressure environment raises additional safety concerns.

An alternative approach is *low-pressure supercritical HTL (LP-HTL)*, requiring high process temperatures like supercritical HTL, but operating at lower pressures. It has shown high efficiency in the depolymerization of both low-density and high-density PE and PP. The approach proves to be safer and more cost-efficient compared to supercritical HTL, offering a promising avenue for effective and sustainable depolymerization of PE and PP plastics during the hydrothermal liquefaction process.

3.2.2 Technological development stage
HTL has seen significant development with respect to both research and commercial applications. Various research institutes and universities, including PNNL (Pacific Northwest National Laboratory) [24], work on maximizing efficiency, yield, and product quality. Companies such as Brightmark in the USA [25] and Licella in Australia [26] have already implemented HTL on a commercial scale, showcasing its viability as practical solution for transforming plastic waste into valuable products.

3.2.3 Advantages compared to pyrolysis and incineration

Laredo et al. [27] investigated potential benefits and drawbacks of HTL as a sustainable option for waste treatment, assessing economic and environmental performance against other plastic-recycling technologies. They found that sub-critical HTL had higher energy ratios (energy output to input) compared to incineration and pyrolysis but slightly lower ones than mechanical recycling. This indicates that HTL can be an energy-efficient process for plastic-waste conversion. GHG emissions associated with HTL were found to be significantly lower than those of pyrolysis and considerably lower than incineration. Comparing the value of output products indicates higher economic returns for HTL than for alternative methods.

For LP-HTL, the study showed an even better environmental performance, with the lowest GHG emissions among all evaluated methods (71% lower than for fuels derived from crude oil and 27% lower than for pyrolysis). This points out LP-HTL as a highly sustainable approach for plastic-waste treatment, minimizing its carbon footprint.

A further advantage of HTL is the ease of separating the produced oils into gasoline and diesel fuels through distillation. This eliminates the need for transporting the oil to external refineries for further upgrading or separation and reduces logistics complexity and costs. [27]

HTL (but not LP-HTL) is also suitable for processing hard-to-recycle plastics such as PVC and could, hence, be combined with other prefixed processes to treat hard-to-recycle plastic residues generated by those. [27]

Summarizing, HTL, particularly in the form of LP-HTL, emerges as a promising waste treatment technology. Its potential for higher energy efficiency, lower GHG emissions, and economic viability positions it as a compelling alternative to incineration, mechanical recycling, fuel production from crude oil, and pyrolysis.

3.2.4 Current challenges to be overcome before commercialization of technology

For optimal resource recovery, pre-sorting of plastic waste and removal of impurities are necessary. This additional step adds complexity to the recycling process but helps to achieve higher-quality outputs. The residues generated during HTL must be handled and disposed appropriately to minimize potential negative environmental impacts.

Recovery of the catalyst material during the recycling process can pose logistical and operational challenges. The deactivation of the catalyst over time can decrease process efficiency. Replacing the catalyst presents additional costs and process complexities that need to be carefully managed. [15]

3.2.5 Further development

Ongoing research aims at advancing process optimization and catalyst development. Process optimization focuses on improving yield and quality of the obtained fuels by adjusting parameters such as temperature, feed ratio of plastics to biomass, and reaction time. Additionally, reactor design using innovative materials resistant to clogging, pressure, and corrosion is crucial for efficient and reliable operations. [15]

Catalyst development is key to enhance efficiency and adaptability of the method, aiming at materials that effectively decompose multiple types of polymers, show high catalytic activity and enable easy recovery.[15]

3.3 Advanced oxidation gasification

3.3.1 Technology description

Advanced oxidation gasification allows to convert plastics into fuels at ambient temperature and pressure, leading the way towards a new standard for utilizing energy from plastic waste. This innovative approach harnesses reactive species like hydroxyl radicals ($\cdot$OH) to transform plastic polymers into organic products, including carboxylic acid and sulfonic acid. These organic products have significant potential as valuable carbon resources in the chemical industry. Additionally, the process generates CO_2 as a by-product, which can be further converted into acetic acid using photoreduction or electrocatalysis, and solid char and coke residues.[15] Depending on the plastic types used as input, different technologies and process conditions are applied, leading to different oxidation reactions and main output products, see Figure 5.

Type of plastics	Technology	System	Conditions	Products	Yield	Refs.
LDPE	Photocatalysis	polyacrylamide grafted TiO_2	UV light	CO_2	/	(Liang et al., 2013)
PET	Photocatalysis	Carbon Nitride/Nickel Phosphide	Solar light, T – 25 °C	H_2	77.2 µmol/g	(Uekert et al., 2019)
PET	Photocatalysis	CdS/CdO_x	Visible light	H_2	278.2 mmol/g	(Uekert et al., 2018)
LDPE	Photocatalysis	ZnO	UV light	CO_2	/	(Kamalian et al., 2020)
PVC	Fenton	$FeCl_3$, H_2O_2	T – 50 °C, C/S Ratio – 8.0	C_1-C_2 acids	82.5%	(Chow et al., 2017)
LDPE	Fenton	$FeCl_3$, H_2O_2	Chlorosulfuric acid – 2.5%, No light	C_1-C_4 acids	62.4%	(Chow et al., 2016)
PE	Fenton	$FeCl_3$, H_2O_2	UV-Vis light, pH – 2.5, Time – 2 h	CO_2	> 99%	(Chow et al., 2018)
PS	Photo-Fenton	$FeCl_3$, H_2O_2	UV light, Time – 300 min	CO_2	89.0%	(Feng et al., 2011)
PVA	Electrocatalysis	H_3PO_4	T – 100 °C, External voltage – 0.55 V	H_2	9.5 µmol/min	(Hori et al., 2020)
PVC	Electrocatalysis	TiO_2/graphite cathode,	T – 100 °C, pH – 3.0, Oxygen flow – 40 mL/min, Time – 6 h, Applied potentia – −0.7 V	Carboxylic acid	75.0%	(Miao et al., 2020)
PP	Solar Thermo-coupled electrocatalysis	NaOH, KOH	T – 350 °C, Time – 60 min, External voltage – 1.5 V	Gas	33.1%	(Jiang et al., 2020)

LDPE: Low density polyethylene; PET: Polyethylene terephthalate; PVC: Polyvinyl chloride; PE: Polyethylene; PS: Polystyrene; PVA: Polyvinyl alcohol. PP: Polypropylene; T: Temperature

Figure 5. *Fuel conversion from plastics via advanced oxidation process [15]*

Photocatalytic oxidation relies on the use of specific catalysts, such as TiO_2, ZnO, or CdS, to initiate the oxidation process when exposed to UV or solar light. This technique is particularly suitable for plastic types like LDPE, PLA, PET, and PVC and leads to the formation of fuels or organic acids. These products are valuable in various applications, including as energy sources or raw materials for the chemical industry.

Fenton oxidation employs catalysts such as Fe^{2+} and H_2O_2 to facilitate the oxidation of plastic molecules. It is effective for plastic types such as PVC, LDPE, and HDPE and has carboxylic acids as the primary output. These acids find use in various chemical processes or as intermediates for further reactions.

Electrocatalytic oxidation utilizes H_3PO_4 as catalyst or a TiO_2/C cathode, depending on the specific plastic feedstock. This process occurs through either direct or indirect oxidation. In direct oxidation, the plastic molecules are attacked by ·OH radicals generated through water discharge on the anode surface. In the indirect oxidation route, strong oxidizing intermediates playing a crucial role. Plastic types like PVC, PVA and PP can be subjected to electrocatalytic oxidation. The method has the advantage of potentially producing single products, such as H_2 or carboxylic acids, which can be utilized directly as fuels. This eliminates the need for additional post-treatment steps and enhances the efficiency of the process.

3.3.2 Technological development stage

At present, advanced oxidation gasification is primarily implemented in waste water treatment companies like Esco International [28]. However, it holds great potential as method to convert plastic into fuel and is currently investigated extensively.

3.3.3 Advantages compared to conventional pyrolysis

Advanced oxidation gasification offers significant advantages over conventional pyrolysis techniques for plastic-to-fuel conversion. The conversion can be done at room temperature and pressure, leading to substantial reductions in energy consumption compared to heat treatment methods. The controllability of the process ensures efficient plastic conversion and high product purity.

Photocatalytic oxidation stands out for its controllability and environmental friendliness, as it does not require additional oxidants, contributing to more sustainable and eco-friendly plastic-to-fuel conversion. Fenton oxidation offers the advantage of being conducted at mild reaction conditions, which not only simplifies the process but also reduces energy requirements and associated costs. For electrocatalytic oxidation, the fuel yield can be further optimized by adjusting the voltage and utilizing specific electrode materials, providing flexibility and efficiency in plastic-to-fuel conversion. [15]

3.3.4 Current challenges to be overcome and further development

The reaction process relies on highly efficient catalysts, but the resulting liquid products often have relatively low calorific values. Research efforts are directed at modulating the active sites on catalyst surfaces and optimizing catalyst design to overcome this drawback. This level of control not only facilitates the selective breakdown of chemical bonds in polymers but also enables the targeted conversion of desired fuels, leading to improved fuel quality and efficiency. Currently, advanced oxidation gasification has high costs due to the need for catalysts and additives. Finding ways to reduce these costs without compromising process efficiency is an area of ongoing research.

During processing, the reactor has a tendency to clog. This calls for improvements in reactor design to ensure smooth and uninterrupted operation.

Photocatalytic oxidation offers controllability, but its CO_2 reduction potential is limited. The efficiency of converting plastic waste into multi-carbon fuels can also be improved. Fenton oxidation, although effective, requires large amounts of hydrogen peroxide, leading to higher operating costs. Electrocatalytic oxidation faces challenges such as rather short electrode lifetime, necessitating regular replacement. The high energy needs of the process must also be addressed for better cost-effectiveness and sustainability.[15]

4 Wood waste from the construction and demolition sector

In 2021, wood waste accounted for approximately 13% of all construction and demolition waste in Norway, amounting to over 235.000 tonnes. Over half of this amount was sent to incineration.[29] In addition, there were about 281.000 tonnes of wood waste from household waste, 80-90% of which were sent to incineration.[30] This indicates a high potential for innovative approaches for material recycling. However, there exist various qualities of wood waste, and suitable methods for their treatment and recycling are called for. In this section, we describe two examples, chemical leaching to decontaminate CCA-impregnated wood before further treatment, and wood-to-fiberboard recycling. In addition to production of particle- or chipboard, collected waste wood can be transformed into cellulose pulp for paper mills or textile companies [31], composted, or used to create pallet blocks or wood-cement blocks for construction applications [32].

4.1 Chemical leaching process for decontamination of CCA-treated wood

4.1.1 Technology description

Chromated Copper Arsenate (CCA) treatment of wood enhances durability and resistance against insects and fungi. The chemicals utilized are toxic towards organisms and can pose environmental risks if discharged. The treated wood usually qualifies as hazardous waste [33]. CCA was widely used since the 1970s but was banned for wood impregnation in September 2001 [34]. It has since been replaced by treatment methods with lower toxicity profiles, including alkaline copper quaternary (ACQ) and copper azole (CA) treatments, where copper is present in the form of copper ethanolamine. More recently, micronized copper quaternary (MCQ) and micronized copper azole (MCA) treatment methods were introduced, using a suspension of copper-carbonate particles.

Chemical leaching has been developed to decontaminate CCA-treated wood. The process removes the coating from the wood, resulting in recovered wood that can be sold or used for composting, burning for energy production, ethanol production.

First, the wood is sorted, cleaned and reduced to smaller pieces to enhance leaching efficiency. Next, acid is applied through spraying, immersion or soaking. During this leaching process, the acid interacts with the preservatives in the wood, causing the contaminants to dissolve into the leachate. Several types of chemicals can be used. A study by Blais et al. at the University of Quebec suggests that sulphuric acid is the most cost-effective option, with good extraction yields for metals. The leachate containing the contaminants is then separated from the wood residue through draining or filtration. Finally, an electrolytic deposition or ion exchange takes place to remove copper and chromium from the leachate and to reduce the environmental impact of the extracted contaminants.[35]

4.1.2 Technological development stage

The University of Toronto, Canada, has conducted pilot-scale investigations on the technology in question. These initial studies have demonstrated the economic promise of the technology, but further research is required to delve deeper into its potential.[36]

4.1.3 Advantages compared to landfilling

Blais et al., analysed the costs of decontamination and compared them to the costs of landfilling in the United States, showing that the CCA leaching process is economically comparable to landfilling the waste.[35]

The laboratory-scale process demonstrated efficacy in successfully removing metals from a range of CCA-, ACQ-, CA-, and MCQ-treated wood wastes. This suggests potential for future utilization also after phasing out CCA-treated wood.[36] Extending the process to the pilot scale is a promising outlook for its practical implementation to address metal contamination in various wood waste streams.

4.1.4 Current challenges to be overcome before commercialization of technology

The residue leachate is highly toxic and must be managed responsibly to prevent any adverse environmental or health impacts. Implementing appropriate disposal methods, such as treatment or containment, is vital.

Wood waste in Norway often consists of a mixture of various treated and untreated woods, as shown by a sample analysis by the Norwegian Institute of Bioeconomy Research [37]. Existing studies mainly analysed treatment of sorted wood waste, with little to no attention to economic and technical viability of the process when treating more diverse waste.

4.1.5 Further development

Additional studies should be conducted to assess feasibility and effectiveness of the leaching process in treating mixed wood waste that contains several types of copper-based treatments. As a next step, it is important to develop efficient and reliable methods for decontaminating unsorted wood, leading to reduced overall expenses associated with the complete treatment and recycling chain for wood waste.[36]

4.2 Wood-to-fiberboard recycling

4.2.1 Technology description

Wood-to-fiberboard recycling involves several steps. First, the wood is milled to prepare it for further processing. Then, it is cleaned to remove potentially present pollutants, such as metals.[38] Following this, the wood is chipped and pressed into a mat, combined with resins. The wood particles are then agglomerated using adhesives, using heat and pressure to create the final fiberboard product.[39]

There are specific requirements on the type of wood feedstock that is feasible. It includes various industrial packaging items like fruit and wine crates, pallets, as well as bulky wood waste such as furniture, wardrobes, and desks. Additionally, wood scraps from processing, chipboard panels, trunks, branches [38], and wood waste from building construction and demolition processes can be used [32]. Due to potential contamination concerns, wood impregnated with chemicals cannot currently be recycled into new fiberboard.

4.2.2 Technological development stage

Mechanical wood recycling has reached a mature stage and is widely adopted by numerous companies in Europe. One prominent example is Stokkermill, an Italy-based company known for its commercial implementation of this recycling method.[38] Community-based platforms like Rilegno [32] play a vital role in connecting the wood packaging supply chain with recycling companies, facilitating efficient and sustainable recycling of wood. Several European companies are actively engaged in wood-recycling initiatives. For instance, Unilin [40], based in Belgium, became a prominent player in the sector. Another example is Veolia [41], a UK-based company specializing in environmental services, including wood recycling. The Norwegian company Omtre [42] also works on finding various industrial solutions for industrial processing and repurposing/recycling of wood waste. The companies contribute significantly to a circular economy by effectively managing wood waste and transforming it to valuable resources, thus reducing the environmental impacts of wood disposal.

4.2.3 Advantages compared to incineration or landfilling

Mechanical recycling uses physical processes. For untreated wood, no complex chemical treatment or expensive equipment is required, making the process relatively straightforward. This simplicity makes it easier for Norwegian fiberboard producers and other interested parties to adapt and implement the recycling process within their operations.

Wood is a renewable resource and reusing it through mechanical recycling can reduce demand for new timber. This alleviates pressure on forests and contributes to sustainable resource management. However, wood waste is currently mostly used as fuel in WtE/biomass combustion plants for heat or heat and power production. Material recycling of wood might therefore reduce the feedstock available for such plants.

4.2.4 Current challenges to be overcome

Mechanical recycling of untreated wood requires a prior sorting step to separate chemically treated wood from untreated wood. Otherwise, the recycling process may be compromised, leading to potential contamination and reduced efficiency. Construction and demolition waste, a significant source of wood

waste, typically contains about 8% chemically treated wood waste. This is a considerably-sized fraction that would need to be excluded from the recycling process, which limits overall effectiveness of mechanical recycling in handling the entire wood waste stream. Effective wood-waste collection schemes must be put in place to ensure proper segregation of post-consumer wood waste or direct collection of industrial waste.

In a Norwegian context, further efforts should focus on assessing and developing sufficient domestic capacity to handle and recycle wood waste. This concerns, for example, economic viability of recycling processes, establishment of industrial actors and exploration of other suitable waste-management practices. There still may be a need to export the wood waste to other countries with appropriate recycling facilities until necessary capacity is developed within Norway. However, exporting wood waste introduces additional transportation emissions, which would need to be evaluated against emissions generated by alternative disposal methods like incineration. Life Cycle Assessment (LCA) can help to determine the environmental impacts associated with different waste management options.

4.2.5 Further development

Mechanical recycling methods for untreated wood hold promise and potential for further advancements in sustainability and waste management practices. While there are some challenges to be addressed, such as potential infrastructure limitations and the exclusion of chemically treated wood, there are several factors that indicate a positive outlook.

Furthermore, collaboration between various stakeholders, including government bodies, the wood industry, recycling companies, and research institutions, can drive the future development of wood recycling. By pooling expertise, resources, and knowledge, it is possible to find innovative solutions and to address the challenges more effectively.

5 Used textiles and textile waste

5.1 Fiber2Fiber recycling

Fiber2Fiber (F2F) recycling refers to various technologies for recycling textiles into new textiles. In this report, F2F recycling specifically includes mechanical F2F and chemical F2F technologies.

Mechanical F2F is a mature technology that involves tearing apart fibers, reattaching them, and forming a new sliver (continuous bundle of untwisted fiber). The process starts with sorting the material by type and color, removing non-conforming materials. The garment is then torn into smaller fragments to be shredded or cut. Next, the mass is carded to align the fibers and produce a sliver. Blending follows, where recycled fibers are combined with virgin or regenerated cellulosic/synthetic fibers and spun to produce yarn for fabric production.[43] Currently, the process is commercially practiced for cotton, wool, and cashmere [43] by companies like Renewcell (Sweden) [44] and Lenzing (Austria) [45].

The process is established and scalable, with lower costs compared to chemical or bio-based processes. However, each recycling loop degrades textile quality due to fiber shortening, making it a linear recycling scheme. It has strict input requirements on fiber composition and purity [46], which most garments in the market do not meet as they consist of synthetic fibers or a mix of several fiber types [47].

Chemical F2F is a more recent textile recycling approach that includes monomer and polymer recycling, which will be explained in the following.

5.1.1 Monomer Recycling

5.1.1.1 Technology description

Monomer recycling involves breaking down the polymer chain of synthetic textile fibers to obtain intact monomers. Common methods include hydrolysis (for polymers containing carbonyl groups) and pyrolysis (for polymers without carbonyl groups).[48] Further chemical-recycling-to-monomer approaches exist that are less explored or more expensive, such as alcoholysis, glycolysis, ammonolysis, aminolysis, as well as biological processes like biological decomposition, enzymatic depolymerization, and fermentation.[43]

After monomer recycling, the obtained monomers are resynthesized into virgin-quality polymers, which are then extruded into filaments. These filaments are further processed and spun into yarns.[49]

5.1.1.2 Technological development stage

Currently, monomer recycling is primarily used for synthetic fibers. The method has the potential to be expanded to other fiber types such as cellulose and wool, but this has not yet resulted in textiles.[43]

Ecopet, a subsidiary of Teijin, have implemented monomer recycling practices in their operations. They focus on post-industrial undyed PET textiles, such as fabric waste generated during manufacturing processes. One notable aspect of their approach is the use of sustainable catalysts, such as Mg-Al double oxides pellets, to break down PET polymers into monomers. Ecopet operates recycled polyester yarn factories in Taiwan, China, and Thailand, alongside their OEM factory.[50]

HAVEP is an example of a company that successfully applies monomer recycling in an industrial setting. They specialize in the production of ECONYL fibers made from recycled Nylon 6. The recycling process repurposes discarded materials like old carpets and fishing nets, which are rich sources of Nylon 6. HAVEP break down these materials and extract the monomers for subsequent polymerization into new fibers.[51]

Considering Nylon as textile component, it is important to distinguish between Nylon 6 and Nylon 6.6. Nylon 6 consists of a single monomer, allowing successful commercial recycling. Recycling processes for Nylon 6 are available, and monomers can be recovered to produce new Nylon 6-based textiles. Nylon 6.6, on the other hand, consists of two different monomers, which presents challenges in the recycling process. As of now, commercial recycling options for Nylon 6.6 are limited, and alternative solutions must be explored to effectively recycle this specific type of Nylon.[49]

5.1.1.3 Advantages compared to landfilling

The recovered monomers can be reassembled into high-quality polymers that are equivalent to virgin materials, thus closing the loop in the textile-production chain.[51] This holds immense potential for reducing the reliance on fossil fuels for producing virgin polymers. Integrating monomer recycling into the textile industry not only addresses the growing concern of textile waste management but also aligns with the broader sustainability goals of reducing carbon emissions and mitigating resource depletion.

5.1.1.4 Current challenges to be overcome before commercialization of technology

Polyester fabrics containing dyes present a challenge for closed-loop recycling. Dyes can interfere with the recycling process and affect quality and color of the resulting recycled polymer. Hence, sorting or removal of dyes is necessary before further processing, and techniques such as the use of sodium formaldehyde sulfoxylate have been proposed. This additional step adds complexity and cost to the recycling process.[43]

Monomer recycling is energy intensive due to, for example, high processing temperatures during hydrolysis and pyrolysis. This adds to the environmental impact of the recycling process and can contribute to GHG emissions if the energy is derived from non-renewable sources.[43]

Implementing monomer recycling technologies and establishing necessary infrastructure can be expensive. Processes to break down textiles into monomers, purify the monomers, and synthesize them into new polymers require specialized equipment, facilities, and skilled personnel. These factors lead to higher production costs compared to conventional textile manufacturing.[43]

Currently, monomer recycling is primarily applicable to synthetic fibers. Expanding the technology to include a wider range of fiber types, especially those derived from natural sources, raises technological and logistical challenges that need to be overcome.[43]

5.1.2 Polymer recycling

5.1.2.1 Technology description

Polymer recycling preserves the integrity of the polymer, allowing it to be spun into fabrics without breaking it down into monomers.[43] The process involves mechanical shredding of the recovered textile, followed by chemical dissolution using specific solvents to create a liquid pulp. The liquid pulp is then extruded into fibers that are woven into fabrics.[53]

Polymer recycling can be applied to various types of fibers, including cellulose-based fibers, synthetic fibers, and fiber blends (section 5.1.3). Input materials include post-consumer textiles (also dyed ones), industrial textile and garment waste, and discarded clothing. Certain cellulosic by-products like orange peels, sugar cane straw, cow manure, and dairy waste can also be transformed into non-recyclable fabrics using polymer recycling. Process outputs include textile fibers, dyed textile fibers, and dissolving pulp for fiber spinning.[43] Residues generated in the process vary depending on the input materials and include dyes, pigments, additives (like flame retardants and plasticizers), fillers and reinforcements (like calcium carbonate and fibers), finishing agents (like water repellents and stain-resistant coatings), contaminants (like dirt and oils), and degradation products (smaller polymer fragments or breakdown by-products).[54]

5.1.2.2 Technological development stage

Chemical polymer recycling is successfully implemented by EVRNU, a company based in Seattle, USA. They specialize in recycling cotton and transform it to their proprietary fiber Nucycle™.[53] Renewcell in Sweden are also actively engaged in polymer recycling. They produce Circulose®, a dissolving pulp, which can be used to manufacture various types of regenerated fibers, including viscose, lyocell, modal, acetate, and other man-made cellulosic fibers (rayon).[55] Currently, both EVRNU and Renewcell focus on processing materials with high cellulosic content, such as cotton. Commercial recycling of synthetic fibers and fiber blends remains to be implemented.

5.1.2.3 Advantages compared to incineration and landfilling

Chemical recycling of polyester consumes approximately 12 MJ/kg of energy. While this is higher than for mechanical recycling, it is considerably less than for producing virgin polyester. This means that chemical recycling offers a more energy-efficient approach and can contribute to reducing environmental impacts associated with polyester production.[43]

The technology is compatible with multiple waste fractions, meaning it can effectively process various types of textile waste. This versatility allows for a more comprehensive approach to recycling and reduces the need for separate waste management streams.[43]

Traditional cotton production consumes substantial amounts of water, whereas polymer recycling minimizes the need for new raw material and reduces water consumption. The process operates within a closed-loop system, contributing to a more sustainable and circular economy. By recycling textiles into new polymer-based materials, the process helps conserve resources and reduces the reliance on virgin raw materials. It supports a circular model where waste is transformed into valuable products, lowering the environmental impact of textile disposal.[53]

5.1.2.4 Current challenges to be overcome before commercialization of technology

Chemical recycling of textiles generates considerable residues, which can vary depending on the input and output materials. Proper removal of hardware parts and dyes is necessary, and solvents may have toxic properties. While some solvents can be reused in certain processes, their effectiveness may vary, and finding efficient solvent reuse methods can be challenging. Introducing ionic liquid solvents, which operate at lower temperatures, reduces environmental impacts, but their high costs are a barrier to widespread adoption.[43]

To dissolve the textile materials and to facilitate the chemical processes, a large amount of water is needed compared to other recycling methods. This can strain water resources, and additional wastewater treatment may be required to address any pollutants or contaminants. The process has also a significant energy consumption. This energy demand contributes to the overall environmental footprint of the recycling process, potentially offsetting some of the environmental benefits gained from diverting textiles and textile waste away from incineration or landfill.[43]

The cost of output fibers from chemical recycling tends to be higher compared to virgin fibers. This cost disparity hinders broader adoption and scalability of the technology. Efforts are underway to increase scale and reduce costs, achieving greater economic viability. But governmental policies and investments are called for to support development and upscaling of chemical recycling technologies in the textile industry.[43]

5.1.3 Separation of fibre blends

As mentioned earlier, most garments are made of synthetic fibers or a combination of different types of fibers. Therefore, separation of fibers is crucial for efficient and cost-effective recycling processes.

Typically, either the polyester is dissolved from the cotton or the cotton from the polyester to recover the individual constituents of poly-cotton blends for further processing. Separating *polyester* from poly-cotton blends begins with depolymerization of the polyethylene terephthalate (PET) component. This can be achieved using sodium hydroxide, which breaks down polyester fibers and allows to recover the cellulose. It yields two main outputs of monomers, ethylene glycol and terephthalic acid. The remaining blend residue can be utilized as fuel or further processed to extract other chemicals. An alternative approach uses bio-based deep eutectic solvents such as glycerol-choline chloride to dissolve the polyester component, enabling extraction of cellulose for subsequent textile production.[43]

To dissolve the *cellulose* component, ionic liquids, a type of solvent composed of liquid-state salts, have been utilized. The resulting undissolved solid polyester can be recycled with traditional melt spinning techniques while the broken-down cellulose and wool keratin can be regenerated through wet spinning.[56] In the case of denim waste, where polyester and cotton fibers are commonly found in the fabric, switchable hydrophilicity solvents are used. They have the unique property of changing their affinity for water, enabling

a selective separation of polyester from cotton fibers.[43] The process generates several outputs, including the regenerated solvent, the extracted polyester, and the recovered cotton after the drying stage.[57]

Separating fiber blends with solvents can result in high recovery rates of various textile components but is expensive due to the high costs of these solvents. However, some solvents can be regenerated.[43]

Swedish industry group Södra owns OnceMore®, the world's first large-scale recycling process for blended fabrics. The process extracts the cotton fraction from poly-cotton blends and combines it with cellulose from wood. This yields a dissolving pulp which can be used in the production of viscose and lyoncell materials.[58] Also Infinited Fiber, a Finnish company [59], has successfully implemented a commercially viable process for separating fiber blends.[60]

5.1.4 Further development

Key challenges to be overcome for successful upscaling of F2F recycling (both mechanical and chemical recycling) include a reduction of costs and of the volume of chemical solvents used in the process. Additionally, improving solubility of both fiber components and enhancing the yield of the recycling process are crucial. It is also important to minimize negative impacts of mechanical shredding and treatment on the physical properties of the fibers. New technologies based on tracing and big data can greatly facilitate sorting of textile waste, improving efficiency and scalability of separation processes.[60]

Ultimately, these efforts facilitate closing the loop in textile recycling, where materials can be continuously reused, leading to a more sustainable and circular industry. However, reducing the amount of textile waste generated in the first place is paramount. A vital step is the promotion of more conscious consumption and a shift away from fast-fashion mentality.

5.2 Microbial polyester hydrolases

5.2.1 Technology description

Hydrolases belong to a class of enzymes that facilitate hydrolysis reactions, where the introduction of water leads to the breakdown of a molecule into smaller constituents.[61] Several hydrolases, including PHL7, HiC cutinase, TfCut2, Cut190, Est119, FsC, and LCC, have been identified for their ability to degrade PET, a common component of plastic and synthetic textile materials. After its discovery in Japan in 2012, the LLC PET-hydrolytic enzyme held the position as the most effective hydrolase. Recently, the PHL7 enzyme, discovered by a research institute in Leipzig, Germany, has surpassed the effectiveness even of engineered variants of LLC. It degrades amorphous plastic packaging in less than 24 hours.[62] This rapid hydrolysis occurs when the enzyme is exposed to an aqueous medium under atmospheric pressure and is most efficient within a temperature range of 50°C to 72°C. The process breaks down PET into terephthalic acid (TPA) and ethylene glycol (EG), which can be used as feedstocks for production of new PET. This establishes a closed-loop recycling system.[63]

5.2.2 Technological development stage

Large-scale commercial implementation of microbial PET recycling is still limited, but enterprises such as Carbios [61], a company based in France, and Samsara [64], an Australian company, lead the way. Carbios produces transparent PET bottles using monomers derived from the depolymerization of PET plastic waste as well as PET polyester textile waste at the pilot stage. This paved the way for the launch of Carbios' industrial demonstration plant in 2021, to validate technical, environmental, and economic performance of their enzymatic PET recycling process. The validation prepares construction and implementation of their first industrial unit. Additionally, Carbios has plans to sell their enzymes, showcasing the potential for wider industry adoption of their technology.[65, 66] Samsara has secured research funding for development and construction of their recycling facility.[64]

These activities contribute to technological advancement of microbial PET hydrolases and commercialization of PET recycling. The companies' progress and investments in research and infrastructure highlight the growing importance and potential of microbial PET recycling in addressing the global plastic waste challenge.

5.2.3 Advantages compared to incineration or landfilling

Microbial PET hydrolases operate efficiently at lower temperatures. This allows for significant energy savings compared to other technologies that often require high temperatures or energy-intensive processes.[62]

Similar to chemical monomer recycling (section 5.1.1), microbial PET hydrolases break down plastic waste into its constituent monomers, which can then be used to produce new plastic materials. This closed-loop recycling method ensures that the quality of the recycled plastic remains comparable to that of virgin plastic, reducing the need for extensive additional processing or downgrading of the material.[62] Unlike traditional linear manufacturing processes that result in single-use plastic items, microbial PET recycling allows for multiple (up to forty) new lifecycles of the same product. The longer usability reduces demand for production of new plastic and minimizes the accumulation of plastic waste in landfills or the environment.[62]

Another notable advantage of microbial PET recycling is the potential for further development. Researchers can engineer new enzymes or modify existing ones to broaden the range of plastic types that can be effectively treated. This enables recycling of a more diverse array of plastic materials and contributes to a more comprehensive and sustainable waste management system.[63]

5.2.4 Current challenges to be overcome

The presence of colorants and additives in the plastic feedstock affects the composition of other outputs generated during the degradation process, necessitating proper management and disposal procedures.[63]

Similarly, treating mixed synthetic fibers found in textiles with microbial polyester hydrolases may result in increased residue volumes, necessitating appropriate strategies for their handling and disposal in an environmentally conscious manner.

Existing hydrolases can only degrade amorphous, but not crystalline PET commonly found in stretched PET used for bottles and textiles. The treatment of this plastic type requires an energy-intensive amorphization pre-treatment, which poses a challenge for economic feasibility in the recycling of unsorted PET.[62]

So far, discovery and engineering of enzymes have been focused on PET alone, limiting the overall impact of this recycling method on the global plastic waste stream. Although PET constitutes a significant portion of plastic types currently in use, the exclusive emphasis on PET enzymes hinders the ability to address the broader range of plastic waste present in the environment.[62]

5.2.5 Further development

Microbial textile waste recycling sees promising progress, as exemplified by EU projects such as Miplace [67] and Enzycle [68] advancing recycling methods by harnessing newly discovered enzymes. At the University of Leipzig, Germany, current efforts are directed towards enhancing performance and stability of the PHL7 enzyme. Encouraging progress has been made in developing enzyme variants with higher activity compared to the original wild-type enzymes. Research is also underway to explore pre-treatment methods to enable degradation of stretched PET, a crucial step in the recycling process. Additionally, the projects explore the potential for large-scale enzyme production and for further refining the enzymatic reaction, working towards an operational pilot plant.[62] Other research explores, e.g., utilization of enzymes from bacteria and fungi for efficient PET degradation.[69]

6 Conclusions

This report examined a range of waste recycling technologies with long-term implementation potential, aiming to address the impending challenge of managing large waste volumes and recovering valuable resources efficiently while minimizing environmental harm. It aims to provide a representative selection of process types across the different waste fractions. It is important to note, however, that the research conducted for this report was not exhaustive, and the technology descriptions are based on limited and sometimes one-sided sources, mainly due to their novelty and lack of extensive research.

Generally, it can be stated that sustainable, non-linear waste treatment methods hold substantial potential. Among these, biological waste treatment processes have emerged as particularly promising, provided the technologies reach sufficient maturity and scale-up cost challenges can be overcome. Examples include fly larvae composting practiced by companies like Enterra and PreZero, cultivation of fungi on plastic or food waste by Biohm and various research institutions, and use of microorganisms from the guts of wood-feeding termites to treat wood, plastic, or food waste, which is not commercially practiced yet (see references in the Appendix). Notably, these processes operate at lower temperatures compared to thermal or hydrothermal methods, resulting in energy and cost savings, and they generate fewer environmentally problematic residues than chemical approaches. The rather limited exploration of biological processes so far, compared to mechanical or hydrothermal methods, suggests that their potential may not be fully recognized yet.

In conclusion, while this report provides an overview of several waste recycling technologies with long-term potential, it must be recognized that further research, collaboration, and investments are required to fully harness their benefits. A significant share of the reviewed technologies has not been widely implemented on a commercial scale yet, underscoring the need for further research and development. Continued exploration, particularly in the realm of biological waste treatment, holds great promise for improved resource recovery, environmental preservation, and a more sustainable future.

Acknowledgments

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Appendix

Treatment technology	Waste fraction	Treatment category	Technology provider	Source
Fly larvae composting	Food	Biological	Enterra (Canada) AgriProtein (USA) PreZero (USA)	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf
Worm composting	Food	Biological	MyNoke and Hungry Bin (New Zealand)	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf
Worm composting	Food, Mixed waste, Plastic	Biological	University of Queensland (Australia)	Sun, J., Prabhu, A., Aroney, S. T. N., & Rinke, C. (2022). Insights into plastic biodegradation: Community composition and functional capabilities of the superworm (Zophobas morio) microbiome in styrofoam feeding trials. Microbial Genomics, 8(6). doi:10.1099/mgen.0.000842
Mechanical biological treatment (MBT)	Food, Mixed Waste, Plastic	Biological, Mechanical	Komptech (Germany)	Mechanical biological treatment of waste. (2013). www.ciwem.org Komptech. MBT plant (mixed waste). https://www.komptech.com/en/plants/mbt-plant/#/ (accessed Jun. 7, 2023)
Mono-incineration	Food, Mixed waste, Sewage	Thermal	Sludge2energy (Germany)	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf
Cultivation of fungi on waste	Plastic	Biological	University of Yale (US) Kew university (Netherlands)	Gallagher, K. (2022, December 14). Plastic-eating mushrooms: Species, Benefits, Impact. https://www.treehugger.com/mushroom-that-eats-plastic-5121023 Russell, J. R., Huang, J., Anand, P., et al. (2011). Biodegradation of polyester polyurethane by endophytic fungi. Applied and Environmental Microbiology, 77(17), 6076–6084. doi:10.1128/AEM.00521-11 Kew Royal Botanic Gardens. (2023, May 17). Plastic-eating fungi thriving in man-made "plastisphere" may help tackle global waste. https://phys.org/news/2023-05-plastic-eating-fungi-man-made-plastisphere-tackle.html
Cultivation of fungi on waste	Food	Biological	Biohm (UK)	Yang, L., Park, D., & Qin, Z. (2021). Material Function of Mycelium-Based Bio-Composite: A Review. In *Frontiers in Materials* (Vol. 8). Frontiers Media S.A. doi: 10.3389/fmats.2021.737377 Attias, N., Livne, A., & Abitbol, T. (2021). State of the art, recent advances, and challenges in the field of fungal mycelium materials: a snapshot of the 2021 Mini Meeting. Fungal Biology and Biotechnology, 8(1). doi: 10.1186/s40694-021-00118-3
Succinic acid production	Food	Biological	Research on laboratory scale in Sweden	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf
Swill feed	Food	Biological	Past practice; stopped by legislation after foot and mouth disease	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf

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Treatment technology	Waste fraction	Treatment category	Technology provider	Source
Acidogenous fermentation	Food	Biological	Pilot scale exists. Nears full-scale implementation (Europe, USA). "Open mixed culture" concept tested at lab scale (Sweden).	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf
Cultivation of larvae on waste	Food	Biological	Nearly industrial scale (Invertapro, Norway))	https://www.invertapro.com/en
Direct micro-organism cultivation (Single Cell Protein (SCP))	Food	Biological	/	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf
Microorganism cultivation (SCP) from methane	Food	Biological	Industrial scale (UK, USA, Denmark)	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf
Dark fermentation	Food	Biological	Pilot scale (Indian Institute of Technology Kharagpur)	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf
Methanation of hydrogen (bio-gas efficiency increase)	Food	Biological	Pilot scale tests (Sweden)	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf
Gasification + fermentation	Food	Biological, Gasification, Thermal	Multiple pilot cases and laboratory tests. Commercially implemented by some companies	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf Figueras, J., Benbelkacem, H., Dumas, C., & Buffiere, P. (2023). Syngas biomethanation: In a transfer limited process, is CO inhibition an issue? Waste Management, 162, 36–42. Henstra, A. M., Sipma, J., Rinzema, A., & Stams, A. J. (2007). Microbiology of synthesis gas fermentation for biofuel production. Current Opinion in Biotechnology, 18(3), 200–206. Bredwell, M. D., Srivastava, P., & Worden, R. M. (1999). Reactor design issues for synthesis-gas fermentations. Biotechnology Progress, 15(5), 834–844. doi: 10.1021/bp990108m
Electroporation	Food	Biological	Ongoing university research	Anderzén, C.. (2018). Framtidens återvinningsprocesser för matavfall. (In Swedish) http://databas.resource-sip.se/storage/4H0bThyNIkxHMoTCVHQ3akziiGkX3I9EzWN0yxlH.pdf

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Treatment technology	Waste fraction	Treatment category	Technology provider	Source
Catalytic cracking	Plastic	Pyrolysis	Agylix (Norway) Plastic energy (UK) Recycling technologies (UK), Brightmark (US)	Li, N., Liu, H., Cheng, Z., Yan, B., Chen, G., & Wang, S. (2022). Conversion of plastic waste into fuels: A critical review. Journal of Hazardous Materials, 424. doi: 10.1016/j.jhazmat.2021.127460
Gasification + MTO process (methanol to olefin)	Plastic	Catalytic chemical, Gasification	Honeywell (US)	Reznichenko, A., & Harlin, A. (2022). Next generation of polyolefin plastics: improving sustainability with existing and novel feedstock base. SN Applied Sciences, 4(4). doi: 10.1007/s42452-022-04991-4 Gogate, M. R. (2019). Methanol-to-olefins process technology: current status and future prospects. Petroleum Science and Technology, 37(5), 559–565. Harris, K., Grim, R. G., & Tao, L. (2021). A Comparative Techno-Economic Analysis of Renewable Methanol Synthesis Pathways from Biomass and CO_2. Preprint. https://www.nrel.gov/docs/fy21osti/78547.pdf
Catalytic cracking	Plastic	Pyrolysis	Agylix (Norway) Plastic energy (UK) Recycling technologies (UK) Brightmark (US)	Li, N., Liu, H., Cheng, Z., Yan, B., Chen, G., & Wang, S. (2022). Conversion of plastic waste into fuels: A critical review. Journal of Hazardous Materials, 424. doi: 10.1016/j.jhazmat.2021.127460
Conventional Gasification	Food, Plastic, Mixtures	Gasification	Inentec (US) Jgc (Japan)	Haiqi Environ. (2022, July 27). What is the difference between pyrolysis and gasification? https://www.biogasifier.com/knowledge/what-is-the-difference-between-pyrolysis-and-gasification.html
Bacterial poly-ester hydrolases (IsPETase, PE-H, Mors1)	Mixtures, Plastic, Textile	Biological	/	Richter, P. K., Blázquez-Sánchez, P., Zhao, Z., et al. (2023). Structure and function of the metagenomic plastic-degrading polyester hydrolase PHL7 bound to its product. Nature Communications, 14(1), 1905.
Microorganisms in the guts of wood-feeding termites	Mixtures, Plastic, Wood	Biological	/	Al-Tohamy, R., Ali, S. S., Zhang, M., Sameh, M., Zahoor, Mahmoud, Y. A. G., Waleed, N., Okasha, K. M., Sun, S., & Sun, J. (2023). Can wood-feeding termites solve the environmental bottleneck caused by plastics? A critical state-of-the-art review. Journal of Environmental Management, 326.
End-of-life F2F	Textile	Biological, Chemical, Hydrolysis	/	Sanchis-Sebastiá, M., Ruuth, E., Stigsson, L., Galbe, M., & Wallberg, O. (2021). Novel sustainable alternatives for the fashion industry: A method of chemically recycling waste textiles via acid hydrolysis. Waste Management, 121, 248–254.
Acid hydrolysis	Textile	Chemical, Hydrolysis	/	Sanchis-Sebastiá, M., Ruuth, E., Stigsson, L. et al. (2021). Novel sustainable alternatives for the fashion industry: A method of chemically recycling waste textiles via acid hydrolysis. Waste Management, 121, 248–254.
Chemical recycling to monomer	Plastic, Textile	Biological, Chemical	/	/
F2F wool (regenerated wool)	Textile	Chemical	/	Ribul, M., Lanot, A., Tommencioni Pisapia, C., Purnell, P., McQueen-Mason, S. J., & Baurley, S. (2021). Mechanical, chemical, biological: Moving towards closed-loop bio-based recycling in a circular economy of sustainable textiles. Journal of Cleaner Production, 326. doi: 10.1016/j.jclepro.2021.129325

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Oxyfuel combustion	Food, Mixtures, Plastic	Thermal	Linde Engineering (Germany) Västerås mälarenergi plant (Sweden)	Saha, M. & Dally, B. B. (2022). Fundamentals of Low Emission Flameless Combustion and Its Applications (Seyed Ehsan Hosseini, Ed.). Elsevier. doi: 10.1016/C2020-0-02292-9 Nemitallah, M. A., Habib, M. A., Badr, H. M., et al. (2017). Oxy-fuel combustion technology: current status, applications, and trends. International Journal of Energy Research, 41(12), 1670–1708.
Agent-based + building-information modeling	Construction/demolition waste (CDW)	Coordination	/	Yu, Y., Yazan, D. M., Bhochhibhoya, S., & Volker, L. (2021). Towards Circular Economy through Industrial Symbiosis in the Dutch construction industry: A case of recycled concrete aggregates. Journal of Cleaner Production, 293. doi: 10.1016/j.jclepro.2021.126083
Robotic waste sorting and recycling	CDW	Coordination	/	Wang, Z., Li, H., & Yang, X. (2020). Vision-based robotic system for on-site construction and demolition waste sorting and recycling. Journal of Building Engineering, 32. doi: 10.1016/j.jobe.2020.101769
Hydrothermal gasification	Food	Hydrothermal	Grtgaz (France)	Okolie, J. A., Nanda, S., Dalai, A. K., Berruti, F., & Kozinski, J. A. (2020). A review on subcritical and supercritical water gasification of biogenic, polymeric and petroleum wastes to hydrogen-rich synthesis gas. Renewable and Sustainable Energy Reviews, 119.
Wood Plastic Composites (WPCs) production	CDW, Mixtures, Plastic, Wood	Chemical, Thermal	Centre for Materials Research of İzmir Institute of Technology (Turkey) – H2020 project URBANREC	Basalp, D., Tihminlioglu, F., Sofuoglu, S. C., Inal, F., & Sofuoglu, A. (2020). Utilization of Municipal Plastic and Wood Waste in Industrial Manufacturing of Wood Plastic Composites. Waste and Biomass Valorization, 11(10), 5419–5430. doi: 10.1007/s12649-020-00986-7 Liikanen, M., Grönman, K., Deviatkin, I. et al. (2019). Construction and demolition waste as a raw material for wood polymer composites – Assessment of environmental impacts. J of Cleaner Production, 225, 716–727.
Alkali-activated building materials from CDW	Brick, Glass, CDW, Concrete	Chemical, Mechanical	Universidad del Valle, Cali (Columbia)	Robayo-Salazar, R. A., Rivera, J. F., & Mejía de Gutiérrez, R. (2017). Alkali-activated building materials made with recycled construction and demolition wastes. Construction and Building Materials, 149, 130–138.
Brick waste to mortar	Brick, CDW	Chemical, Mechanical	State Univ. of Santa Catarina (UDESC), Joinville, SC (Brazil)	Schackow, A., Stringari, D., Senff, L., Correia, S. L., & Segadães, A. M. (2015). Influence of fired clay brick waste additions on the durability of mortars. Cement and Concrete Composites, 62, 82–89.
PVC flooring recycling	CDW, Mixtures, Plastic	Chemical, Mechanical	Clean EOL products: Gerflor (France) Paprec (France) Soiled EOL products: Sols PVC pro (France) AgPR (Germany)	Montagnier, R. (2021, June 28). Floor to floor investit 18 millions d'euros dans un site de recyclage des plastiques dans l'Isère. *L'Usine Nouvelle*. https://www.usinenouvelle.com/article/floor-to-floor-va-investir-18-millions-d-euros-dans-un-site-de-recyclage-des-plastiques-a-salaise-sur-sanne-isere.N1114344 Gerflor. A collection and recycling solution to each stage of the life cycle. https://www.gerflor.com/environment-by-gerflor/recycling.html Paprec. A series of investments for the plastics division. https://www.paprec.com/en/a-series-of-investments-for-the-plastics-division/ Sols PVC pro. La collecte et le recyclage des sols PVC. http://solspvcpro.com/environnement-et-sante/collecte-et-recyclage.html AgPR. https://agpr.de/en/overview/

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