Enzymatic recycling of polyethylene

A barrier study for Norway

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Summary

Plastic is an essential material in modern society. Its durability and versatility, however, pose significant environmental challenges, as plastic waste persists in the environment for decades or longer. Current recycling methods, such as mechanical or chemical recycling, face a range of limitations. Enzymatic recycling is an emerging, promising solution that uses enzymes to depolymerize plastics into their original monomers, allowing indefinite recycling without considerable quality loss.

Despite its potential, enzymatic recycling faces multiple barriers. Technical challenges include the slow degradation of non-hydrolysable plastics, enzyme instability at industrial temperatures, and contamination in waste streams. Economic barriers involve the high cost of enzymes and specially designed plastics. Regulatory uncertainty, limited domestic recycling infrastructure, and social factors such as low awareness and acceptance further constrain adoption. Environmental considerations, such as energy use for controlled processing conditions, must also be addressed. To unlock the potential of enzymatic recycling in Norway, coordinated efforts are required across research, industry, and policy.

Norway has the opportunity to become a global leader in enzymatic recycling by combining scientific innovation, industrial implementation, and forward-looking policy. Successfully scaling enzymatic recycling could reduce greenhouse gas emissions, improve resource efficiency, and strengthen the country's circular economy while providing high-quality, endlessly recyclable plastics.

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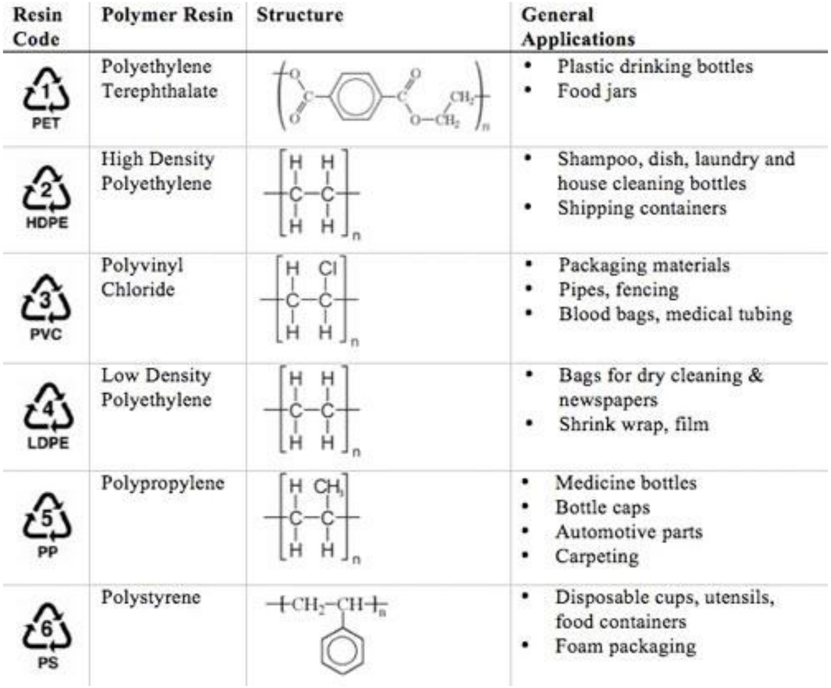
Introduction

Plastic has transformed industries and become an essential part of modern life. From everyday products like packaging, clothing, and mobile phones to critical materials used in buildings, vehicles, and agricultural equipment, plastic is everywhere. It helps extend the shelf life of food, significantly reducing food waste, and its lightweight nature lowers fuel consumption in cars, trucks, and airplanes. In healthcare, plastic is indispensable due to its ability to be easily disinfected and sterilized. But what exactly are plastics?

Plastics are synthetic polymers, meaning they are long chains of repeating structural units known as monomers. These monomers are chemically linked together through a process called polymerization, creating long, flexible chains with diverse properties. By using different monomers, a wide variety of plastic types can be produced, each with unique characteristics. This means that plastic is not a single, uniform material, but rather a diverse group, each with distinct chemical structures and properties. One of the most well-known polymers is polyethylene terephthalate (PET), widely used in beverage bottles and textiles (where it is known as polyester). Polypropylene (PP) is valued for its durability and heat resistance, making it ideal for yogurt cups and food containers. Polystyrene (PS), a lightweight and insulating material, is commonly found in foam packaging and disposable utensils. Polyvinyl chloride (PVC) is widely used in construction due to its strength, flexibility, and resistance to moisture.



Resin Code	Polymer Resin	Structure	General Applications
1 PET	Polyethylene Terephthalate		- Plastic drinking bottles - Food jars
2 HDPE	High Density Polyethylene	$\left[\begin{array}{cc}H & H\\ C- & C\\ H & H\end{array}\right]_n$	- Shampoo, dish, laundry and house cleaning bottles - Shipping containers
3 PVC	Polyvinyl Chloride	$\left[\begin{array}{cc}H & Cl\\ C- & C\\ H & H\end{array}\right]_n$	- Packaging materials - Pipes, fencing - Blood bags, medical tubing
4 LDPE	Low Density Polyethylene	$\left[\begin{array}{cc}H & H\\ C- & C\\ H & H\end{array}\right]_n$	- Bags for dry cleaning & newspapers - Shrink wrap, film
5 PP	Polypropylene	$\left[\begin{array}{cc}H & CH_3\\ C- & C\\ H & H\end{array}\right]_n$	- Medicine bottles - Bottle caps - Automotive parts - Carpeting
6 PS	Polystyrene	$\left[CH_2-CH\right]_n$	- Disposable cups, utensils, food containers - Foam packaging

Figure 1: The most common plastic polymers including their chemical structure and general applications (Illumin Magazine[1])

The most used polymer globally however is polyethylene (PE), accounting for nearly a quarter of all plastic production. PE is a polymer composed of long chains of ethylene monomers (C_2H_4), which give it a simple yet highly versatile structure. The repeating carbon-carbon backbone provides PE with flexibility, durability, and resistance to moisture and chemicals. PE exists in two main forms: low-density polyethylene (LDPE) and high-density polyethylene (HDPE), which differ in molecular arrangement and properties. LDPE has a more branched structure, making it softer and more flexible, ideal for bags or agricultural films. In contrast, HDPE has a more linear and tightly packed structure, giving it higher strength, rigidity, and resistance to UV and chemicals, making it suitable for shampoo bottles or cleaning product containers.

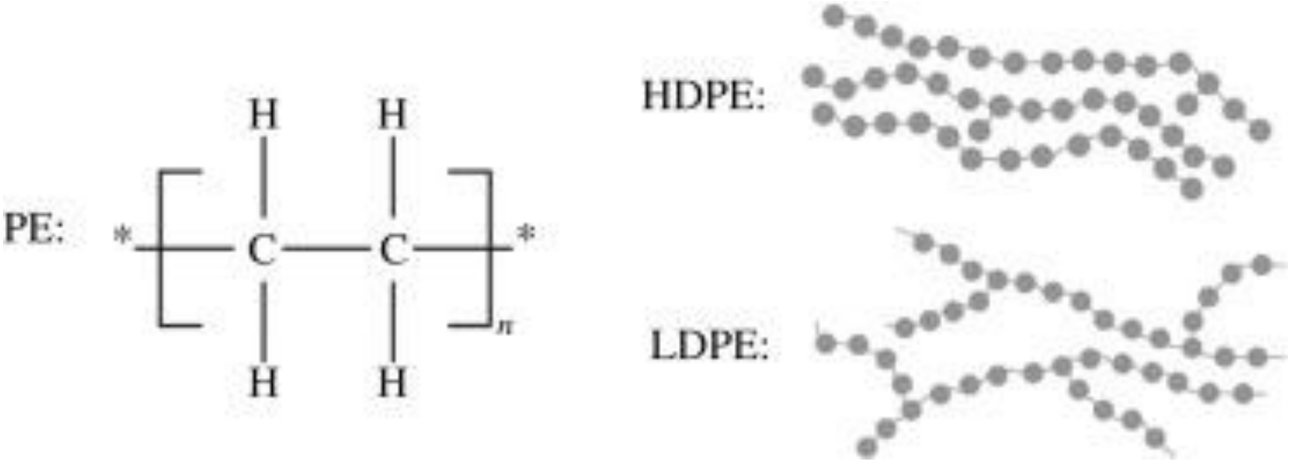


Figure 2: Chemical structure of polyethylene (Baxter et al. 2020[2])

Most plastic types are primarily produced from non-renewable fossil fuels and are designed to be durable. A feature that is advantageous during their use but problematic once they reach the end of their lifecycle. When improperly managed, plastic waste can persist in the environment for centuries due to its slow degradation rate, contributing to pollution. To combat plastic pollution and reduce the extraction of virgin materials, it is crucial to maintain plastics within a circular economy for as long as possible. Recycling plays a central role in achieving this goal. Currently, plastics are predominantly recycled through mechanical methods, with chemical recycling being used to a lesser extent. Both methods, however, have notable limitations. A promising alternative is enzymatic recycling, an emerging technology that offers the potential for more efficient plastic waste management. Despite its promise, enzymatic recycling faces several challenges that must be addressed before it can be widely adopted.

This study presents a systematic review of the key barriers and drivers influencing the scaling up and commercialization of enzymatic recycling of PE in Norway. It examines critical barriers across technical, economic, regulatory, social, and environmental dimensions, offering practical solutions to overcome these challenges. By highlighting these factors, the study aims to serve as a valuable resource for researchers, industry stakeholders, and policymakers working to enhance plastic recycling through innovative technologies.

Background

Plastic production and waste generation

Plastic production has increased sharply over the past decades. In 1950, global plastic production was just 2 megatons (Mt)[3], but by 2023, it had surged to 413.8 Mt[4] and by 2050, it is expected to have surpassed 800 Mt[5]. China is the world's largest plastic producer, accounting for one-third of global output, while Asia as a whole produces more than half of all plastic worldwide. In contrast, Europe plays a smaller role, contributing 12.3% of global production, or 54 Mt in 2023. Although global plastic production continues to rise, Europe has seen a decline of nearly 10 Mt in annual production over the past six years. Within Europe, Germany leads as the largest producer, followed by Belgium, France, and the Netherlands[4]. Norway has only three producers of plastic and produces an estimated 0.13 Mt[6], most of which is exported, making the country heavily reliant on plastic imports.

It is estimated that approximately 3.1 million tons of plastic products are currently in use in Norway, spanning a wide range of applications, from packaging and electronics to construction materials, automotive parts, textiles, and household items[6]. Of this, about one-third is used in the construction sector. The lifespan of plastic products varies greatly depending on their application: while construction materials and car parts can remain in use for several decades, items like electronics and household goods are typically used for only a few years, and packaging often has a lifespan of just a few days before being discarded as waste. As a result, nearly 40% of the 540,000 tons of plastic waste generated annually in Norway is packaging waste, whereas construction materials account for only 7% of plastic waste generated[6]. Approximately 140,000 tons (26%) of plastic waste generated in Norway are LDPE and 43,000 tons (8%) are HDPE, primarily from packaging, with smaller amounts from agricultural films (only LDPE)[7]. This means that in total, polyethylene makes up roughly one-third of all plastic waste in Norway[7].

Recycling methods

To reduce dependency on fossil resources and enhance circularity, plastic recycling is becoming ever more important. However, only 9% of all plastics ever produced have been recycled, while the remainder has been either incinerated, sent to landfills, or accumulated the natural environment[3].

Mechanical recycling

Today, when plastic is referred to as "recycled", it typically involves mechanical recycling, the most common and simplest form of plastic recycling. In this process, the plastic waste is first collected and then sorted by type based on properties such as color, chemical composition, and density. The sorted plastics are then shredded into small flakes, thoroughly washed, dried, and granulated before being re-extruded into new plastic products[8].

While mechanical recycling is well-established, cost-effective, and relatively low in energy and resource consumption, it presents several limitations. The quality of the recycled plastic is highly dependent on the quality and purity of the input material, necessitating extensive pre-treatment. It is particularly inefficient for multi-layer or heterogeneous plastics. One of the main challenges is the reduction in plastic quality with each recycling cycle. Most plastics can only undergo two to three cycles before their properties deteriorate, requiring the addition of virgin, fossil-based plastic to retain the desired properties[9]. Furthermore, recycled plastics may retain additives from their previous use, which can restrict their application, especially in sensitive areas like food and medicine. As a result, much of the plastic is downcycled into products of lower quality, with reduced performance and economic value.

Chemical recycling

Another recycling method is chemical recycling, which refers to various technologies that use chemical agents or processes to break down plastic into its basic chemical building blocks (monomers). These monomers can then be used to produce new plastic in the same way as virgin material or, alternatively, be converted into fuels. The term chemical recycling encompasses several methods, each with their own unique principles. Among these, depolymerization, pyrolysis and gasification are the most prominent methods. Depolymerization involves reversing the polymerization process through chemical reactions, breaking down polymers into individual monomers that can be re-polymerized to form new plastic materials. Pyrolysis uses high temperature in the absence of oxygen to convert plastics into liquid or gaseous products called pyrolysis oil, which can be used as fuel or for heat production. Gasification transforms plastics into synthesis gas, a mixture of hydrogen and carbon monoxide, under high heat and controlled oxygen conditions. The so-called syngas can be used in various industrial processes, such as the production of fertilizers, methanol or ammonia.

One of the key advantages of chemical recycling is its ability to handle low-quality or mixed plastic waste that cannot be processed mechanically. Unlike mechanical recycling, chemical methods are less sensitive to contamination and allow for the separation of additives. Moreover, the quality of the plastic made from chemically recycled material is comparable to virgin plastic, allowing it to undergo endless recycling cycles and still produce high-quality products. However, chemical recycling comes with several challenges. The processes often require high temperatures and complex chemical reactions, making them energy-intensive and raising concerns about their environmental sustainability. Several life cycle analyses indicate that while chemical recycling has a lower environmental footprint than producing virgin plastics or incineration, it generally has a higher impact than mechanical recycling[10]. Additionally, high investment cost and technological complexity remain major barriers.

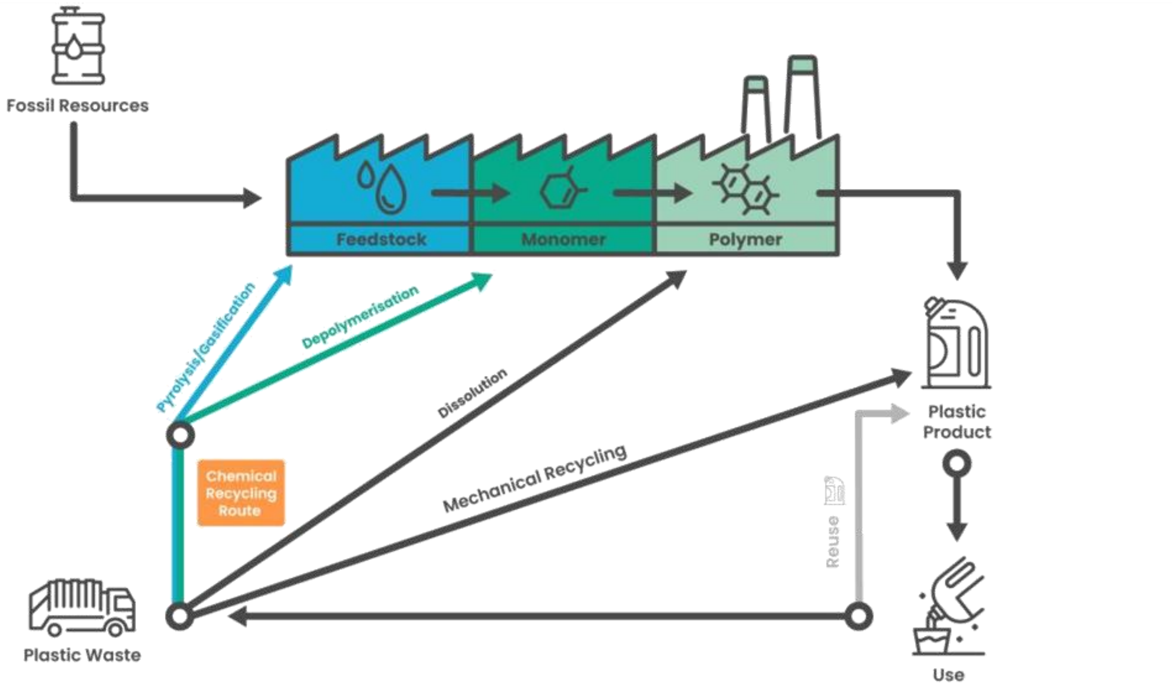


Figure 3: Production and recycling pathways of plastics (Plastics Europe[11])

Of the 54 Mt of plastic produced in Europe in 2023, approximately 80% originated from fossil-based virgin materials, while 20% came from recycled sources[4], the vast majority of which was mechanically recycled plastic. Chemical recycling accounted for only 0.2% of Europe's total plastic production[4]. However, numerous chemical recycling facilities are currently planned across Europe, with the potential to scale up production to 2.8 Mt by 2030[11] (equivalent to around 5% of Europe's plastic production in 2023).

Enzymatic recycling

With both mechanical and chemical recycling having a range of limitations regarding plastic type, quality of the recycled material and the energy consumption required in the process, enzymatic recycling is an innovative and promising solution offering a more sustainable approach for managing plastic waste. As the name suggests, enzymatic recycling relies on enzymes to break down plastic. Enzymes are biological catalysts that accelerate chemical reactions without being consumed in the process. The enzymes act like molecular scissors, breaking down complex plastic polymers chains into their original monomers. The resulting monomers can then be repolymerized into new plastic products that maintain the same high quality and properties as virgin plastics. This new way of recycling has the potential to pave the way for more efficient, environmentally friendly, and sustainable plastics waste management.

Where are we today?

Enzymatic recycling appears, on paper, to be a highly promising solution to our growing plastic waste problem. But how close are we to making it a reality? Is it a breakthrough on the horizon, or is it still more science fiction than science fact?

Do we have the necessary enzymes?

Let's take a closer look at enzymes and where they come from. In order to do that, we need to zoom out (but not too much, we are still at a microscopic level).

The primary source of enzymes are microorganisms. Microorganisms are tiny living organisms such as bacteria or fungi. They were the first form of life to appear on Earth around 3.8 billion years ago and since then they have evolved into at least a trillion different species[12]. We can find microorganisms in nearly every environment on Earth: from soil, air and water to harsh environments such as deep-sea vents or hot springs. Microorganisms play a huge role in natural ecosystems, including decomposing organic matter and cycling nutrients. Humans have made use of them for centuries in, for example, cheese production and beer brewing or, more recently, in the pharmaceutical industry.

One of the most powerful ways microorganisms interact with their surroundings is through enzymes. Enzymes are proteins that function as biological catalysts, accelerating chemical reactions without being consumed in the process. They are highly specific, meaning each enzyme typically acts on a particular type of molecule. Over Earth's history, enzymes have evolved to break down a wide range of natural materials. Some of these natural materials are similar to synthetic polymers in that they contain chemical bonds (like esters) that are cleavable by enzymes. It is therefore likely that microorganisms have evolved capabilities for decomposing and utilizing plastics. However, plastics are a relatively recent, human-made invention, having only been in widespread use for less than a century. This means nature has had limited time to evolve enzymes capable of efficiently degrading synthetic polymers. In addition, synthetic polymers are often more durable and resistant to decomposition compared to natural polymers making them less susceptible to breakdown by enzymes[13].

Regardless, a steadily expanding enzymatic toolbox is now being developed to target hydrolysable synthetic polymers. For polyesters, a range of cutinases, carboxylesterases, and lipases have been shown to depolymerize PET as well as biodegradable polymers such as polybutylene terephthalate (PBT), polylactic acid (PLA), and polycaprolactone (PCL) by cleaving ester bonds, primarily at the amorphous regions of the polymer surface [14,15] (see below for more details on enzymatic PET degradation). For nylons, a family of synthetic polymers widely used In textiles, amidases/peptidases (e.g., NylA/NylB/NylC and related 6-aminohexanoate-dimer hydrolases) have been identified to cleave amide linkages in nylon-6/6,6 oligomers and model substrates. However, enzymatic degradation of industrially relevant nylon is still inefficient[16]. In the case of polyurethanes (PU), several polyesterases and urethane hydrolases ("urethanases") from bacterial and fungal sources have been reported to attack polyester-type PU soft segments and certain carbamate linkages[17]. Polyester-type PU, however, remains particularly recalcitrant to enzymatic attacks. Among known enzymes, PU-esterases (PUEs), cutinases, and serine hydrolases have demonstrated the highest activity, especially on PU foams and emulsified substrates[18].

Enzymatic recycling: ongoing projects

To date, no full-scale facility for enzymatic plastic recycling is operational. However, the French company Carbios is currently building the world's first industrial-scale PET enzymatic recycling plant in Longlaville, France (Grand-Est region, near the borders of Belgium, Germany, and Luxembourg)[19]. Since 2021, Carbios has been operating a demonstration plant with a capacity of approximately 250 kg of PET waste per day. The new facility, expected to be operational by 2026, will have a capacity of 50,000 tons per year (almost 150 tons per day). It will be capable of processing materials such as colored bottles, multilayer food trays, and polyester textiles, which are typically difficult to recycle mechanically [19].

The enzyme which Carbios uses is currently the only known enzyme for the effective depolymerization of plastic polymers. In 2016, Japanese scientists discovered a PET degrading bacteria in samples taken at a PET-bottle recycling site. This bacterium was later called *Ideonella sakaiensis,* after the city of Sakai where the samples were taken. The bacterium produces an enzyme called PETase, which is able to depolymerize PET. While the initial enzyme required about seven weeks to break down a piece of PET[20], subsequent discovery of other PETases, combined with enzyme engineering approaches has dramatically improved its efficiency, allowing 95% of PET is be depolymerized in less than 24 hours[19]. The resulting monomers, terephthalic acid (TPA) and ethylene glycol (EG), can be repolymerized using existing industrial facilities without further modification[19]. Carbios' process is estimated to reduce emissions by 51% compared to conventional plastic production[20].

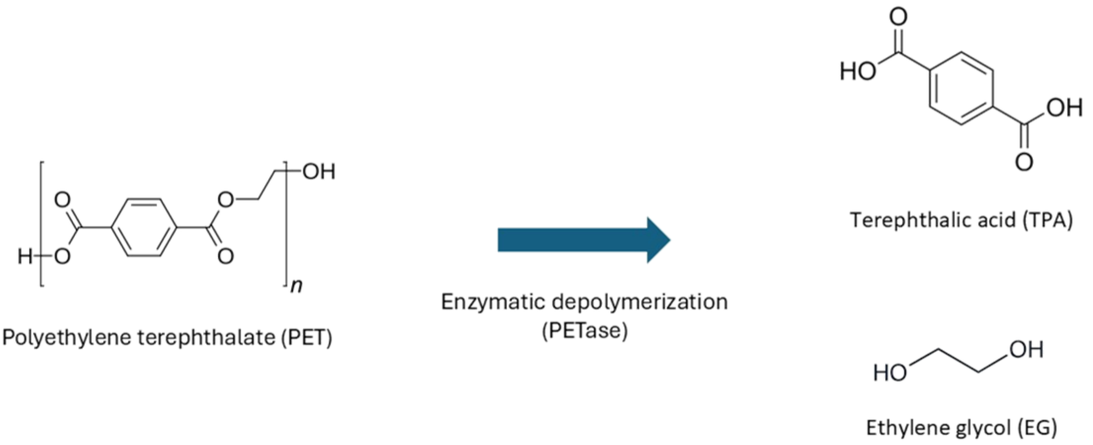


Figure 4: Polyethylene terephthalate (PET) depolymerization into terephthalic acid (TPA) and ethylene glycol (EG) by the enzyme PETase

On the other side of the world, in Australia, the startup Samsara Eco has patented a range of enzymes capable of breaking down hard-to-recycle plastics, including nylon 6,6, mixed fibers, and colored or dyed fabric blends[21]. In 2024, Samsara Eco partnered with lululemon to produce the world's first enzymatically recycled nylon 6,6 product and launched a limited-edition jacket made from enzymatically recycled polyester[22]. The company is now constructing a commercial-scale facility designed to process approximately 20,000 metric tons of nylon 6,6 per year, with operations expected to begin in early 2028[21].

Extensive research is also underway to discover and develop new enzymes capable of depolymerizing more challenging plastic polymers, namely non-hydrolysable plastics such as PE and PP. One such initiative is the Enzyclic-project[23], funded by the Research Council of Norway and running from 2021 to 2026. The project is a collaboration between the Norwegian University of Life Sciences (NMBU), the environmental foundation Bellona, the plastics technology center Norner, textile producer Aclima, the Norwegian Packaging Association (Emballasjeforeningen), and consumer goods company Orkla. In addition to identifying and engineering enzymes that can efficiently degrade resistant plastic types, the project also aims to design new plastics that are specifically tailored for enzymatic recycling and the enzyme developed in the project. If successful, Enzyclic could play a key role in advancing Norway's bioeconomy by enabling lower greenhouse gas emissions, improved resource efficiency, and new industrial opportunities. This report has been developed as part of the Enzyclic project.

Can we make polyethylene more enzymatically recyclable?

Traditional plastics, such as PE, PP, PS and PVC are highly resistant to enzymatic degradation. Instead of focusing solely on discovering new enzymes capable of degrading existing plastic polymers, an alternative approach is to modify the polymers themselves to make them more susceptible to enzymatic degradation.

As previously discussed, PE consists of long carbon–carbon chains without reactive functional groups needed for hydrolysis (see Figure 2). Other plastics such as PP, PS and PVC share this inert carbon–carbon backbone (see Figure 1), which lacks functional groups and makes them highly resistant to biological degradation. These plastics are classified as non-hydrolysable due to their resistance to enzymatic cleavage.

To address this challenge, researchers are exploring ways to incorporate predetermined breaking points in the polyethylene chains during the synthesis of designed-to-recycle polyethylene-like materials. These "weak links" are typically functional groups that can be targeted by enzymes[24]. A low density of such functional groups can be introduced without significantly affecting the crystallinity or desirable mechanical properties of polyethylene. These functional groups are introduced into the polymer chain either during the polymerization of olefins with functional co-monomers or via the polycondensation of long-chain functional monomers.

Advantages and disadvantages of enzymatic recycling

As outlined in the previous chapters, enzymatic recycling is emerging as a promising complementary technology in the transition toward a more circular and sustainable plastics economy by offering an alternative to both mechanical and chemical recycling. It brings several potential advantages but also faces important limitations. Because the technology is still at an early stage of development, understanding both its strengths and its challenges is essential for assessing its future role. This chapter therefore presents an overview of the main advantages and disadvantages of enzymatic recycling and forms the basis for the barrier study presented in the following chapter.

Advantages

1. **High selectivity**: Enzymes can be specifically engineered to target and break down only certain plastic types into their monomers, leaving other polymers and impurities intact. This selectivity reduces the need for sorting by polymer type and allows (partly) recycling of plastic composites (e.g., layered plastics), thereby expanding the range of acceptable waste feedstock. As a result, feedstock costs can be lowered, and the quality of recycled material is enhanced.
2. **Energy efficiency**: Enzymatic depolymerization can be performed at relatively low temperatures and does not require harsh chemicals, significantly reducing energy consumption and greenhouse gas emissions compared to traditional mechanical or chemical recycling methods.
3. **Reduced pretreatment requirements**: Enzymatic recycling minimizes the need for extensive pretreatment of waste, such as the removal of food residues, labels, or the separation of different plastic polymers. This simplification makes the process more efficient and cost-effective.
4. **Infinite recycling potential**: Plastics recycled enzymatically are broken down into their original monomers, which can then be repolymerized into polymers identical to the starting material, i.e. virgin plastic. This enables indefinite recycling without quality loss. Products made from enzymatically recycled plastic will be close to 100% material-recycled and at the same time remain 100% recyclable[13].
5. **Powerful enzyme design tools**: Following the 2024 Nobel Prize in Chemistry awarded to D. Baker, J. Jumper and D. Hassabis for breakthroughs in protein design and structure prediction, a new generation of powerful computational tools has become publicly available[25]. These tools enable the rapid development of novel enzymes with unprecedented activities and tailor-made properties. In the context of plastics recycling, this opens the possibility of designing enzymes that specifically target synthetic polymers and are optimized for industrial conditions, including stability, efficiency and selectivity.

Disadvantages

1. **Early development stage:** Enzymatic recycling is still in the early development stages, and the scalability of the process to meet the demands of large-scale plastic waste management remains a significant challenge.
2. **Limited enzyme availability:** Since plastic polymers are a relatively recent invention, natural enzymes have not had sufficient time to evolve specifically to degrade these materials. Initiatives to design novel plastic degrading enzymes are also in their infancy. This limits the availability of enzymes capable of breaking down plastics[13].
3. **Suboptimal enzyme characteristics:** Even for the plastic polymers where suitable enzymes have been identified, these enzymes often have limitations. They may degrade plastic too slowly, lack the necessary thermal stability, or function only within a narrow temperature range. However, researchers are actively working to optimize enzyme efficiency, enhance their stability, and lower production costs[13].
4. **Low bioavailability of plastic polymers:** While natural polymers such as cellulose, wool or rubber, are easily degraded by enzymes, synthetic plastics are more durable and resistant due to their unique chemical and physical properties[13]. The highly stable carbon-carbon (C-C) backbone without reactive functional groups makes polymers such PE, PP, PS and PVC extremely resistant to enzymatic degradation[26].

Barriers for enzymatic recycling of polyethylene in Norway

For the successful implementation of enzymatic recycling of synthetic polymers, a number of barriers must be addressed. This section focuses specifically on the enzymatic recycling of PE in Norway. PE has been chosen due to its dominant position in the plastics market, its high volume in the waste stream, and the significant challenges associated with its recycling. Norway is used as the geographical frame of reference as this report is developed within the Norwegian research project Enzyclic, funded by the Research Council of Norway. Nevertheless, many of the barriers identified here are equally relevant for other plastic polymers and in other regional contexts.

This section evaluates seven technical, two economic, two regulatory, three social, and one environmental barrier, and proposes practical measures to overcome each of them.

Technical barriers

Technical barriers are related to the technological aspect of the system being studied. These include limitations in the technological maturity, low process efficiency, difficulties in scaling up from lab to industrial scale, insufficient infrastructure or challenges in quality control.

Barriers	How to overcome them
Enzymes cannot break down all plastics: Not all plastic types are susceptible to enzymatic breakdown. Enzymes used in enzymatic recycling are substrate-specific, meaning they are effective only on certain polymers. More complex or chemically stable polymers present a significant challenge due to their strong carbon-carbon bonds and lack of functional groups that enzymes can target.	**Enzyme engineering:** Protein engineering can be employed to develop or enhance enzymes capable of attacking a broader range of plastic polymers. **Enzyme discovery:** A vast diversity of natural enzymes remains unexplored, offering significant potential for identifying new plastic-degrading biocatalysts. **Plastic modification:** Plastics can be chemically or physically pre-treated to introduce functional groups or oxidized sites that can serve as enzymatic attack points.

Enzymes cannot withstand high temperatures: Industrial recycling processes often involve elevated temperatures. Many natural enzymes lose their structure and functionality when exposed to such conditions, which limits their industrial applicability.	**Thermostable enzymes:** By screening organisms living in extreme environments, naturally occurring thermostable enzymes might be discovered. **Protein engineering:** Currently available enzymes can be modified to improve thermal stability while retaining their activity**.** **Process design:** The reactor systems can be optimized to maintain temperature conditions within the enzymes functional range.
Degradation rate too slow: Even when enzymes are capable of breaking down certain plastics, their reaction rate may be too slow to be commercially viable. Slow kinetics reduce throughput and increase processing time and costs.	**Enzyme optimization:** The enzymes' efficiency can be improved through protein engineering. **Process improvement:** Improvements to reaction conditions such as pH, temperature, and mixing can enhance enzymatic activity.
Decreased efficiency due to contamination: Real-world plastic waste is rarely pure. It contains dyes, fillers, additives, other types of polymers, food residues, and other contaminants that can inhibit recycling.	**Selective enzymes:** Enzymes are highly specific and can target polymers even in mixed or contaminated waste streams. This selectivity allows them to function effectively where traditional methods struggle. **Efficient pre-treatment:** Cost-effective pre-treatment steps such as washing, sorting, or selective solvent treatments can remove contaminants which hinder enzyme efficiency. **Integrated systems:** Combining mechanical, chemical, and enzymatic steps can provide a more robust system to handle contaminated waste.
Disrupting conventional recycling: Introducing new types of plastics can interfere with established mechanical recycling systems. This is the case for biodegradable plastics and might also be the case for enzymatically recyclable polymers. These new materials may degrade under conventional processing conditions, contaminate recycled batches, or alter the quality of recycled plastic. If not properly separated, they could undermine the efficiency and economics of existing recycling infrastructure.	**Clear labeling:** Developing a standardized labeling and traceability system to distinguish enzymatically recyclable plastics from conventional ones will facilitate effective sorting. Norway already uses sorting labels for various waste types, providing a foundation that can be expanded to include new plastic categories. **Dedicated waste streams:** Establishing separate collection and processing streams for new plastic types prevent contamination of traditional recycling systems. Clear labeling and consumer guidance are essential to enable accurate sorting at the source. **Polymer design:** When engineering plastics for enzymatic recycling, efforts should also be made to ensure compatibility with conventional recycling

	methods. Designing dual-recyclable plastics can reduce disruption of existing systems.
Adaptability of existing production infrastructure: Existing plastic production facilities are designed for conventional monomers and polymerization processes. Transitioning to plastics engineered for enzymatic recycling may require modifications to equipment, new handling procedures, or entirely new processing lines. Adapting or replacing this infrastructure can be costly and technically challenging, potentially slowing down the adoption of enzymatically recyclable plastics.	**Incremental adaptation:** To encourage the development of new plastics that are compatible with existing equipment or require minimal changes enables gradual integration into current production systems. **Technical support:** Providing manufacturers with access to technical expertise and training to assess and implement necessary modification efficiently can ease the transition to producing enzymatically recyclable plastic polymers.

Economic barriers

These are financial obstacles that prevent the widespread adoption or scaling of technology. They may include high production costs, expensive raw materials, lack of funding or investment, unfavorable cost-benefit ratios, and uncertain market returns.

Barriers	How to overcome them
High cost of enzymes: Enzymatic recycling relies on specialized enzymes that can be expensive to produce. When enzymes are not highly active or stable more enzymes are needed, further driving up cost and limiting commercial viability.	**Enzyme engineering:** Improve enzyme stability, efficiency and specificity through protein engineering. **Policy support:** Subsidies, tax incentives, or public funding for pilot projects can help offset early-stage costs.
High cost of new plastics: To make plastics more susceptible to enzymatic recycling, the polymer structure must often be engineered to include chemical bonds that enzymes can break down more easily. This requires the development of new monomers, which are more complex and more costly to produce than conventional monomers. As a result, plastics designed for enzymatic recyclability may have significantly higher production cost, limiting their competitiveness in the market.	**Scale-up:** By scaling-up production from lab- or small-scale production to industrial scale production, the unit costs of monomers will be reduced and the supply chains optimized. **Market incentives:** Regulatory tools like green procurement policies, subsidies, or extended producer responsibility (EPR) can level the playing field for recyclable plastics. **Life cycle benefits:** Highlighting the long-term savings in waste management and environmental impacts can justify the higher upfront material costs.

Regulatory barriers

These barriers arise from laws, regulations, or policies that limit the implementation or scaling of a new technology. They may include strict environmental regulations, lack of clear guidelines for new technologies, complex approval processes, or insufficient government support.

Barriers	How to overcome them
Lack of regulatory framework: There is currently limited regulatory clarity for enzymatically recycled plastics, particularly when intended for food-contact use. Regulatory bodies may require extensive toxicological and performance data before granting approval, slowing adoption and increasing costs.	**Regulatory engagement:** Working closely with national and EU regulators can help establish clear guidelines. **Demonstrate safety:** Conducting robust testing can prove the safety and purity of recycled outputs. **Pilot approvals:** Focusing on non-food applications initially can provide proof of concept and building data to support food-grade use over time.
No recycling infrastructure in Norway: Currently, Norway lacks recycling infrastructure for post-consumer waste, whether mechanical, chemical, or enzymatic. This absence of domestic recycling capacity hinders the implementation of advanced technologies like enzymatic recycling.	**Limit export of plastic waste:** Banning or limiting the export of plastic waste encourages domestic processing instead. **Public investment:** Innovation funds can be established especially for novel recycling methods like enzymatic recycling. In addition, public funding and green investment programs can be used to support pilot and demonstration plants.

Social barriers

These are obstacles resulting from human attitudes, behaviors, and social norms. They may include lack of awareness, resistance to new technologies, insufficient stakeholder engagement, or limited consumer willingness to pay for recycled products.

Barriers	How to overcome them
Low public awareness and acceptance: Enzymatic recycling is largely unknown to the general public and even to many in the plastics industry. This can lead to skepticism or lack of demand for products made from enzymatically recycled materials.	**Education campaigns:** Launching public awareness campaigns highlighting the benefits and safety of enzymatic recycling can increase public awareness. **Transparent communication:** Educating consumers and businesses about the environmental benefits of enzymatically recycled plastics using clear labeling and public awareness campaigns will accelerate acceptance. **Showcases:** Demonstrations of successful cases and products made from enzymatically recycled plastics

	can showcase the process and increase public acceptance.
Limited understanding: Even within sustainability and recycling sectors, enzymatic recycling sometimes is misunderstood or seen as unproven. There is limited data on its environmental impacts compared to mechanical or chemical methods.	**LCA studies:** Conducting independent life cycle assessments comparing enzymatic recycling to other recycling methods such as mechanical or chemical recycling can show the sustainability of enzymatic recycling. **Scientific publications:** Sharing findings through peer-reviewed journals and industry events make people aware of the process. **Stakeholder education:** By providing clear, science-based materials, policymakers, researchers, and waste managers are educated about enzymatic recycling.
Inferior performance: Plastics engineered for better recyclability may compromise on certain performance characteristics such as durability, flexibility, clarity, or heat resistance. If these plastics are perceived as inferior to conventional plastics in terms of quality or convenience, consumers and manufacturers may be reluctant to adopt them, especially in applications where performance is critical (e.g., food packaging, electronics, automotive).	**Target non-critical applications:** As a first step, enzymatically recyclable plastics can be introduced in areas where high performance is not essential, such as disposable plastic, to build acceptance of the material. **Incentivize sustainable choice:** Using policy tools like eco-labels, green procurement requirements, or tax incentives can encourage the adoption of recycled materials, even if they might offer slightly different performance.

Environmental barriers

These barriers are related to sustainability and resource availability. They may include negative environmental impacts, high resource consumption (e.g., energy, water), emissions during processing, or challenges in waste management.

Barriers	How to overcome them
Higher environmental impact: Enzymatic recycling may require tightly controlled conditions, such as high temperatures, pressure, or continuous mixing, leading to higher energy use compared to conventional recycling.	**Process conditions:** Optimizing process conditions to operate under milder, more energy-efficient conditions or improve energy efficiency can decrease energy consumption. **Renewable energy:** Powering facilities using renewable energy instead of fossil fuels can reduce the overall carbon footprint.

Outlook and next steps

Enzymatic recycling of PE presents an exciting, yet still largely untapped opportunity for advancing circularity in plastic value chains. This study has identified key technical, economic, regulatory, social and environmental barriers that must be addressed to unlock the potential of enzymatic recycling of PE in Norway.

The greatest challenges lie in the current technical limitations of enzymes to degrade PE and the lack of polymers engineered for enzymatic recyclability. However, emerging research into enzyme engineering and polymer design provides a promising foundation for further development. Looking ahead, several coordinated efforts are needed in enzyme discovery and engineering to identify enzymes capable of depolymerizing plastics efficiently under realistic conditions. Simultaneously, material scientists and polymer chemists should work to design PE and other polymer variants that are more amenable to enzymatic degradation without sacrificing performance.

An additional challenge will be the integration of these new plastic polymers into the current system. For enzymatic recycling to succeed at scale, it is essential that new, enzyme-compatible plastics can be produced and processed using existing infrastructure, or that cost-effective adaptations can be made easily. Close collaboration between polymer developers, recyclers, and policymakers will be needed to align material specifications with operational realities. Furthermore, market incentives, such as eco-modulated fees, recycled content targets, or procurement policies, could accelerate adoption and investment.

Moreover, regulatory frameworks need to be developed and adapted to support the use of enzymatically recycled materials. Currently, there is no specific legal framework in Norway or the EU that addresses enzymatic recycling, particularly for high-risk applications such as food-contact materials. Early engagement with policymakers, alongside collaboration with polymer producers, researchers, and recyclers, will be essential to ensure that emerging regulations are science-based, innovation-friendly, and aligned with market needs. Norway has an opportunity to take a leading role by initiating national-level dialogues that can inform and influence EU policy development. This proactive approach can help ensure that regulation keeps pace with technological progress while maintaining high standards for public health, environmental protection, and consumer confidence.

One final obstacle that must be highlighted is Norway's currently limited capacity for sorting and recycling plastic. This challenge is not unique to enzymatic recycling but affects the entire recycling system. At present, 41% of Norwegian plastic packaging is sent to Germany for recycling, while only 21% is processed domestically[27]. The situation is even more striking for household plastic packaging waste: 71% is recycled in Germany, 18% in Lithuania, and 5% in the Netherlands, with a mere 0.02% recycled in Norway itself[27]. To fully utilize the plastic waste generated within the country, a robust national recycling infrastructure must be developed. Such an infrastructure would allow plastic to be processed through the most suitable method, whether mechanical, chemical, or enzymatic, while retaining its value within Norway's circular economy. The opening of the new Områ sorting facility in the fall of 2025[28] marked an important step forward, but it must be followed by strong, long-term policies that prioritize domestic recycling and ensure plastic remains in closed loops within national borders.

By pursuing these next steps, Norway has the unique opportunity to develop not only a technically viable enzymatic recycling process for plastics, but also the social, economic and regulatory conditions needed to scale it. The path forward is complex but offers substantial environmental and economic benefits.

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