STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 2, 2026
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Next-Generation Polymer Recycling for Circular and Sustainable Plastics

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Abstract

Plastic waste has emerged as a serious global environmental issue because of the enormous quantities produced over the past several decades. Moreover, the continual rise in plastic production, coupled with low recycling rates, results in the steady accumulation of plastic in the environment each year. In addition, manufacturing new polymers consumes substantial amounts of energy and fossil fuel resources. Although renewable energy can reduce emissions to a great extent, still there is a need to consider the environmental impact of material production. In this review, the latest technologies regarding recycling of polymers have been discussed and also different approaches which aim to minimize the plastic waste. Emphasis is placed on the recycling routes that operate at lower temperatures and use electricity instead of heat. These approaches allow better integration with renewable energy sources such as solar and wind power. Enzymatic and electrochemical methods are particularly promising because they can recover high purity monomers while consuming less energy. Advanced recycling represents a significant advancement in waste management technology, offering a viable solution to the challenges posed by plastic waste. Overall, this review shows that combining advanced recycling technologies with intelligent sorting systems can support closed-loop plastic recycling, contributing to a low-carbon materials economy and holds the potential to drive meaningful progress towards a more circular and sustainable economy.

Keywords: Plastic recycling, circular economy, enzymatic depolymerization, AI-based sorting, sustainable polymers

INTRODUCTION

Polymer materials are everywhere because they are light and strong. The same qualities of these materials make it hard to handle them at the end of their life, which leads to pollution that lasts a long time. Global plastic production is projected to reach approximately 460 million tonnes in 2025 and only 9–10% is recycled [1, 2]. The majority of plastic trash either leaks into the environment, gets burned, or is dumped in landfills. Conventional mechanical recycling, which includes sorting, washing, and melting, is well-established but has disadvantages. Many contemporary plastics such as multilayer films are not recycled. Also, additives contaminate output, and polymer chains deteriorate with time [2, 3]. These limits encourage interest in "next-generation" recycling that returns polymers to near-monomer purity for true circularity. Combination of conventional methods with AI-assisted sorting and integration are examples of recent developments [15]. China emerges as the leading contributor of recycling and circular economy in terms of research publication output, followed by the United States and England, reflecting substantial global research engagement [10, 14].

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Received Date: February 12, 2026
Accepted Date: March 05, 2026
Published Date: April 07, 2026

Citation: Nidhi Gupta, Rachit Kumar, Sunil Gupta, Vedant Singh. Next-Generation Polymer Recycling for Circular and Sustainable Plastics. Journal of Polymer & Composites. 2026; 14 (Special Issue 2): S517–S526p.

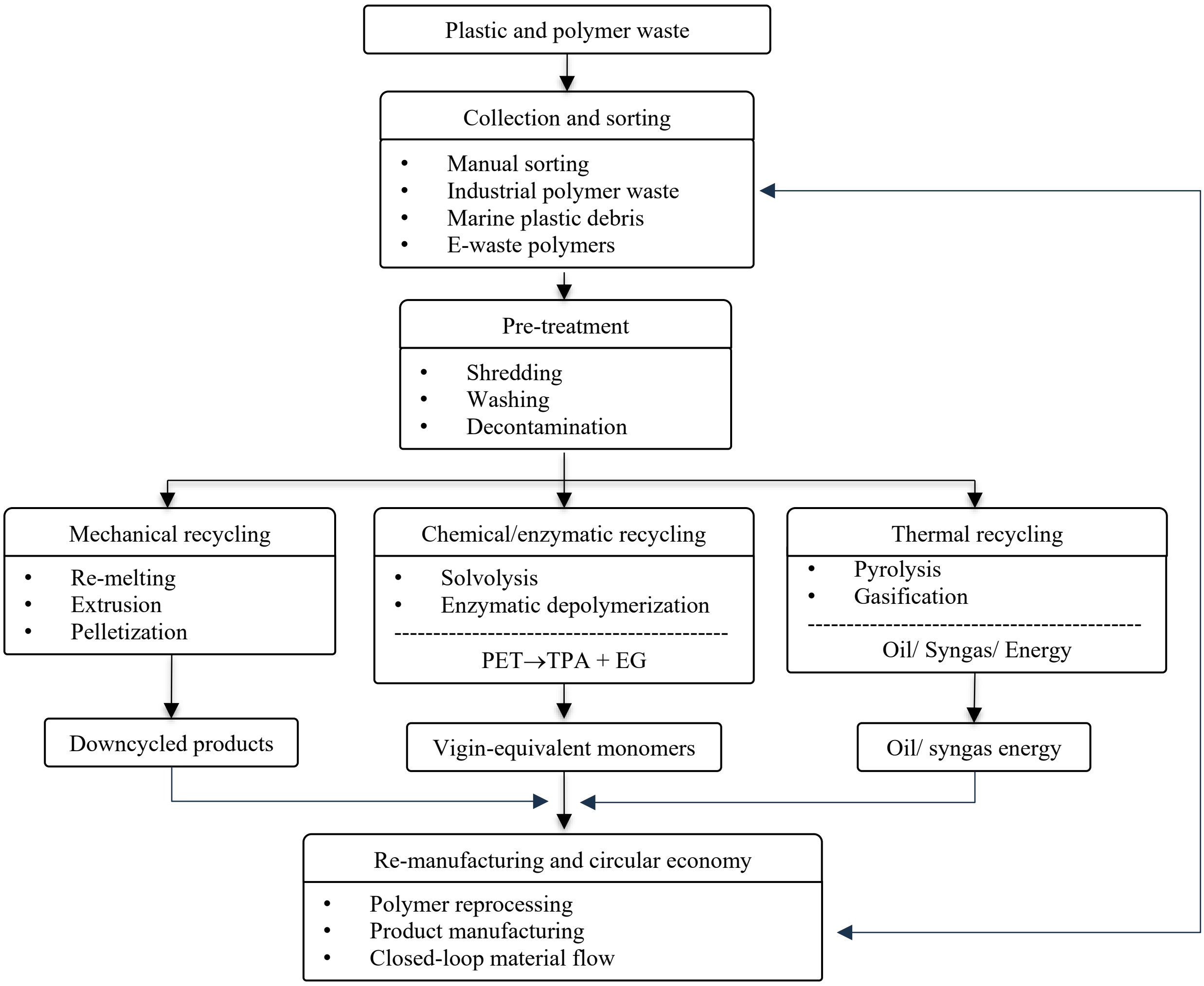

Figure 1. Integrated block diagram of polymer recycling pathways.

This paper presents a review of emerging technologies in polymer recycling and circular economy. Figure 1 represents an integrated block diagram of polymer recycling pathways. To understand the importance of next-generation recycling technologies, it is important to first analyze the strengths and limitations of conventional recycling methods which are currently in practice.

CONVENTIONAL RECYCLING METHODS AND THEIR LIMITATIONS

Mechanical Recycling

Mechanical recycling involves physical processing steps such as sorting, washing, shredding, melting, and extrusion. This method is effective only when the waste stream is clean and contains a single type of polymer. In practice, plastic waste is often mixed and contaminated. Food residues, pigments, fillers, and incompatible polymers reduce the quality of recycled materials. Thermal reprocessing causes polymer degradation through chain scission and oxidation. With each recycling cycle, mechanical strength and durability decrease. As a result, recycled plastics such as PET and HDPE are commonly down cycled into products with lower performance requirements. Figure 1 explains the integrated block diagram of polymer recycling pathways [10].

Traditional Chemical Recycling

Chemical recycling breaks plastics into smaller molecules using heat or catalysts. Pyrolysis is a common method that operates at high temperature without oxygen. This process requires a high amount of energy, which limits its effectiveness for closed-loop recycling.

Thermal Recycling

Thermal recycling methods like gasification convert plastics into synthesis gas at elevated temperatures. The gas produced can be used for energy or production of chemicals. However, the process requires a great amount of energy and complex equipment. Without emission control, it can cause the release of carbon dioxide, which ultimately causes air pollution. So overall, it is not considered sustainable.

Overall, conventional recycling methods face challenges related to energy use, material degradation, and waste heterogeneity. Most approaches struggle to deliver virgin-quality polymers. These limitations reduce their contribution to a fully circular plastic economy.

PET DEGRADATION MECHANISM AND THEIR BIOLOGICAL PATHWAYS

PET is the short for Polyethylene terephthalate, which is one of the most commonly used polymers nowadays. Its properties like strength, durability and chemical stability make it highly resistant to natural degradation and hence it persists in the environment for a very long time. PET is a condensation polymer and it is composed of terephthalic acid and ethylene glycol units joined by ester bonds. It consists of aromatic rings and also highly crystalline in nature which limits water penetration and slows spontaneous hydrolysis. Due to this, it accumulates in landfills and natural ecosystems if not properly managed. Biological degradation of PET occurs through the enzymatic hydrolysis. A bacterium called "Ideonella sakaiensis 201-F6" can degrade PET using two enzymes, namely PETase and MHETase. PETase breaks PET into smaller molecules called mono(2-hydroxyethyl) terephthalate (MHET) , and MHETase converts MHET into terephthalic acid (TPA) and ethylene glycol (EG), which can be assimilated as carbon sources [12, 13]. Recent research has focused on improving the performance of these enzymes through protein engineering.

ROLE OF ADVANCED POLYMER RECYCLING IN NET-ZERO ENERGY SYSTEM

Achieving net-zero emissions is not only about clean electricity. Materials also play an important role. Plastic production uses a lot of energy. Most plastics are made from fossil fuels. Because of this, plastic manufacturing releases large amounts of carbon emissions. Reducing these emissions is necessary for long-term climate goals. Advanced polymer recycling helps reduce this problem. It lowers energy consumption. It also reduces the need for new plastic production. Enzymatic recycling works at low temperatures. It uses less energy and allows useful monomers to be recovered. Electrochemical recycling is another effective method. It uses electricity to break down plastics. The process works under mild conditions. When renewable energy is used, emissions are very low. Recycling efficiency improves with better sorting. AI-based sorting systems help remove impurities. This improves performance and reduces energy use. Overall, advanced recycling reduces dependence on virgin plastics. It lowers emissions across the supply chain. It supports a low-carbon and circular material system.

EMERGING POLYMER RECYCLING TECHNOLOGIES

Enzymatic and Biocatalytic Recycling

Enzymatic recycling uses highly selective biocatalysts (e.g. PET hydrolases, cutinases, esterases) to hydrolyze polymers under mild conditions [3, 10]. Polyesters such as PET and PBT are particularly susceptible: enzyme-catalyzed hydrolysis yields the original monomers (terephthalic acid (TPA) and ethylene glycol (EG) for PET) without harsh chemicals. Recent protein engineering and whole-cell biocatalysts have dramatically improved activity and stability. For example, engineered PET hydrolases (e.g. LCC variants) depolymerize 97–98% of semi-crystalline PET in ~10 h at 65°C [10]. In one pilot, *Thermobifida* sp. enzymes processed 5 tonnes of PET to food-grade monomers, reducing energy use by ~80% compared to mechanical recycling [10]. Immobilized enzymes and PETase/MHETase cascade systems allow continuous operation. Importantly, enzymatic processes tolerate colored or contaminated PET feedstocks that would foul mechanical recycling [3]. The output is high-purity monomers: e.g., *Carbios* reports >95% pure TPA recovery.

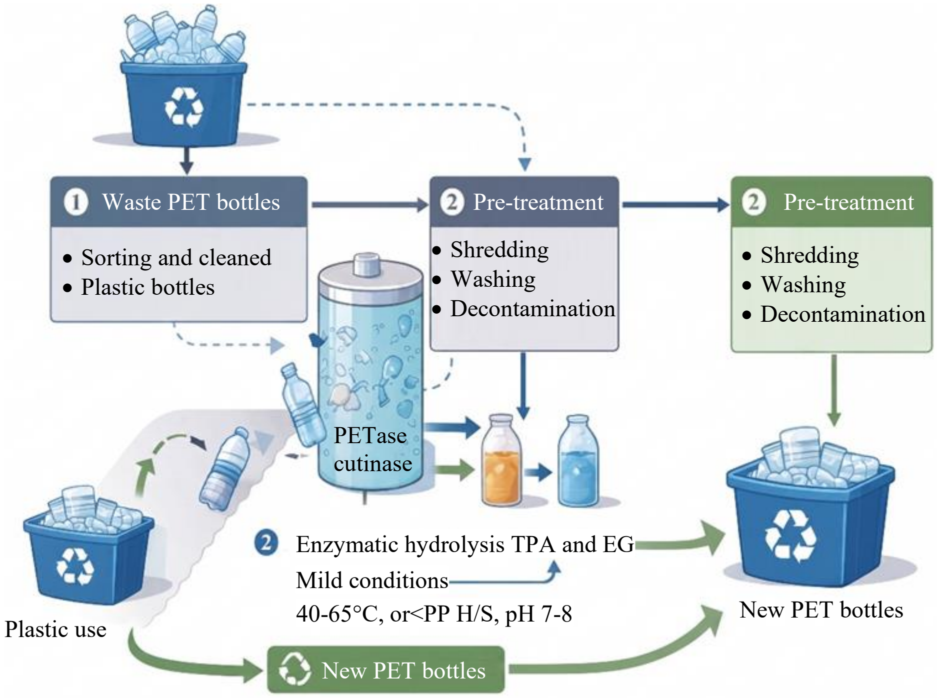

Figure 2. Schematic representation of enzymatic PET depolymerization illustrating PET hydrolysis into mono(2-hydroxyethyl) terephthalate (MHET) by PETase, followed by conversion into terephthalic acid (TPA) and ethylene glycol (EG) via MHETase.

However, enzymes typically act on specific polymers (mostly polyesters) and do not digest polyolefins. Enzymatic rates are slower than thermal processes (hours vs. seconds) and require aqueous systems. Despite these challenges, enzymatic recycling's mild conditions yield high circularity (monomer recovery) with low side reactions [10, 4].

In Figure 2, (1) Waste PET bottles are sorted and cleaned, (2) Enzymatic hydrolysis (e.g. PETase, cutinase) breaks the polymer into TPA and EG, and then the monomers are purified and repolymerized into new PET Plastic [3].

Recent studies continue to enhance enzyme performance: "ultraPETase" variants complete bottle recycling at 30–65°C, and directed evolution has raised hydrolysis rates by several-fold [3]. Whole-cell biocatalysts (yeast or bacteria displaying PET enzymes) avoid expensive enzyme purification, though enzyme production cost remains a barrier. Overall, enzymatic recycling exemplifies a circula**r** pathway: it can recover >90% of original monomer mass under benign conditions [10]. Energy inputs are low (compared to thermal processes), though the need for water and purification adds process cost. Feedstock flexibility is limited to susceptible plastics (mostly PET, PLA, polyurethanes). Economic feasibility improves as enzyme costs fall (now ~\$100–500/kg) and productivity increases [10].

Advanced Chemical Recycling (Solvolysis, Pyrolysis, Gasification)

Solvolysis (Depolymerization in Solvent)

Solvent-driven chemical recycling uses liquid media (water, glycol, methanol, ammonia, ionic liquids, etc.) often with catalysts to depolymerize polymers near their glass transition. This is particularly effective for condensation polymers (PET, polyamides, PC). For instance, PET glycolysis in ethylene glycol yields bis(2-hydroxyethyl) terephthalate (BHET), which can be purified and repolymerized to PET. Similarly, methanolysis yields dimethyl terephthalate (DMT) and terephthalamide aminolysis yields terephthalamide. Solvolysis achieves very high monomer recovery: literature reports >80–90% of PET can be converted back to pure monomer [10].

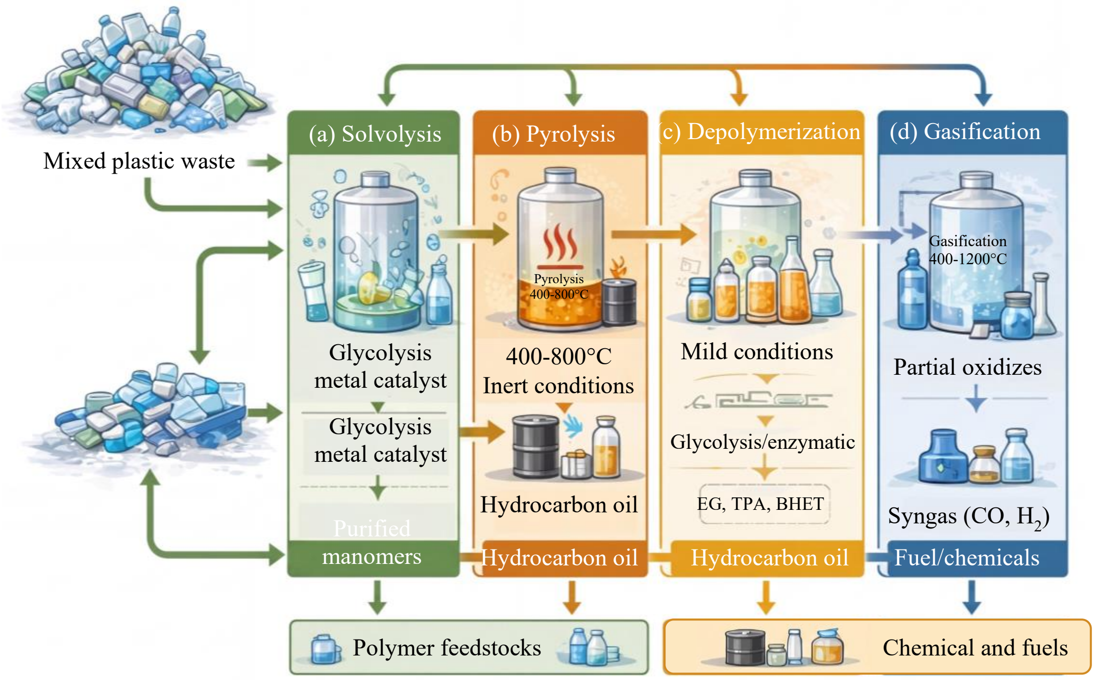

Figure 3. Representation of different thermochemical recycling pathways.

Solvolysis generally requires moderate temperature (100–250°C) and pressure. Innovations include deep eutectic solvents and biobased catalysts to reduce energy inputs. A key advantage is product quality: chemical recycling can yield monomers virtually indistinguishable from virgin feedstock. However, such processes require fairly pure, single-polymer feed and significant solvent purification. Overall circularity is high for targeted plastics, but energy demand is moderate (heating and distillation) and solvent use can add cost.

Pyrolysis

Pyrolysis thermally degrades plastics in an inert atmosphere (no oxygen) at high temperatures (typically 300–700°C). It is mainly applied to mixed polyolefins (PE, PP, PS) and other hard-to-recycle waste. Pyrolysis yields a complex oil (mixture of alkanes, aromatics), lighter gases (syngas), and char. Yields depend on conditions and catalysts: typically, 70–90% of the mass ends up as liquid oil, the rest as gas (H_2, CO, CH_4) and solid residue [9]. Pyrolysis is attractive for its feedstock flexibility: it can process heterogeneous or contaminated waste without sorting [10]. However, pyrolysis rarely yields monomer-grade products – the oil is more suited for fuel or as feedstock for chemical plants (e.g. steam crackers) than direct plastic production. Pyrolysis requires intensive heat, making energy demand high. Gasification is similar but uses limited oxygen/steam to produce syngas ($CO+H_2$) at even higher temperatures (~800–1200°C). Both release significant GHGs if powered by fossil heat. From a circular perspective, pyrolysis/gasification are more "open-loop" (plastic → fuel/energy) than closed-loop. They recover carbon as energy/fuels, but not as original polymers. Recent advances aim to coax more useful chemicals (e.g. hydrogen, carbon nanotubes from pyro-oil) from these methods [8]. Efficiency of pyrolysis (liquid yield ~70–85%) can be high, but the recycled quality is low (fuel rather than polymer). Feedstock flexibility is excellent, but capital and energy costs are high [10].

Advanced Chemical Recycling Via Gasification

This offers a robust thermochemical pathway for valorizing heterogeneous and contaminated plastic waste streams that are unsuitable for mechanical or selective depolymerization routes. In this process, plastics undergo partial oxidation with controlled amounts of oxygen or steam at elevated temperatures (typically 800–1200°C), resulting in complete molecular breakdown and the formation of synthesis gas

(CO and H_2), with minor by-products such as char and tars [8]. The primary advantage of gasification lies in its exceptional feedstock flexibility and tolerance to additives, dyes, and mixed polymers, enabling recovery of plastic-derived carbon in the form of energy carriers or chemical intermediates. As illustrated in Figure 3, solvolysis, pyrolysis, depolymerization and gasification follow distinct thermochemical pathways with varying temperature ranges and product distributions. The products can then be refined into new polymer feedstocks or fuels [9].

Electrochemical Recycling

Electrochemical recycling is an emerging paradigm where electricity (preferably from renewables) drives polymer bond cleavage via redox chemistry [5]. For example, polyethylene terephthalate can be depolymerized in an electrolytic cell into terephthalate salt and ethylene glycol (and ultimately hydrogen and formate) at mild temperatures [5]. One approach uses anodic oxidation of a plastic/polymer slurry, producing value-added products (e.g. formate, hydrogen) and leaving monomers behind. Reports indicate high selectivity: Faradaic efficiencies >95% for hydrogen and formate production have been achieved from model plastic solutions [10]. Compared to thermal routes, electrochemical upcycling can be performed at ~room temperature with no added reagents except electrons, greatly reducing heating energy [5]. This route is highly tunable: choice of electrode and conditions can steer product distribution. Current challenges include developing electrodes compatible with solid plastics and scaling up. So far, electrochemical methods have mainly targeted PET and smaller polyesters, with less work on polyolefins.

AI-Assisted Sorting and Integrated Systems

High-value recycling processes depend strongly on the quality of the input plastic waste. Without proper sorting, advanced recycling methods cannot perform efficiently. Artificial intelligence (AI) and machine learning (ML) have therefore become important tools for improving plastic waste separation. Modern sorting systems use computer vision, near-infrared (NIR) spectroscopy, and robotic systems to identify and separate plastics based on polymer type and color. AI-assisted sorting and integrated systems are revolutionizing industries by combining computer vision, machine learning, and robotics to automate complex, high-speed sorting processes, primarily in waste management, recycling, and manufacturing. These systems, often referred to as AI-powered Materials Recovery Facilities (MRFs), achieve higher purity levels, reduce human error, and improve operational efficiency compared to traditional methods. Utilizing Convolutional Neural Networks (CNNs), these systems analyze visual data to identify materials, even when items are deformed, broken, or overlapped. High-speed robotic arms, capable of up to 80 picks per minute, physically separate identified materials. Integrated Systems (IoT + AI) such as smart bins or automated conveyor lines, collect real-time data, optimizing routes, predicting maintenance needs, and adapting to changing waste compositions. AI identifies, sorts, and separates materials (plastics, paper, metals, glass) with up to 99% accuracy in some cases. Systems can operate 24/7 which reduces manual labour. The overall effect is higher circularity: cleaner feed means higher monomer purity and fewer contaminants in recycled resin. Economically, AI increases capital costs (sensors, robots) but reduces labor and quality losses. In short, AI-driven sorting is an enabler that improves efficiency and scalability of all recycling methods [6]. While highly effective, AI-assisted sorting faces challenges including high initial investment costs, the need for robust data for training models, and the complexity of integrating these technologies into older facilities. Future developments are focusing on full-scale automation of sorting plants, improved handling of multi-material products, and the integration of blockchain for better traceability of recycled materials [6].

Figure 4 shows the schematic representation of an electrochemical recycling whereas Figure 5 represents AI-assisted sorting and integrated recycling systems [6]. Figure 6 explains the criterion for comparison in Table 1, including mechanical, enzymatic, solvolysis, pyrolysis, and gasification routes, highlighting operating temperature ranges, feedstock tolerance, and primary product streams. Pyrolysis (~300–700°C) and gasification (~800–1200°C) enable processing of mixed plastics, whereas enzymatic and solvolysis routes require cleaner feeds and yield high-quality monomers [7, 8].

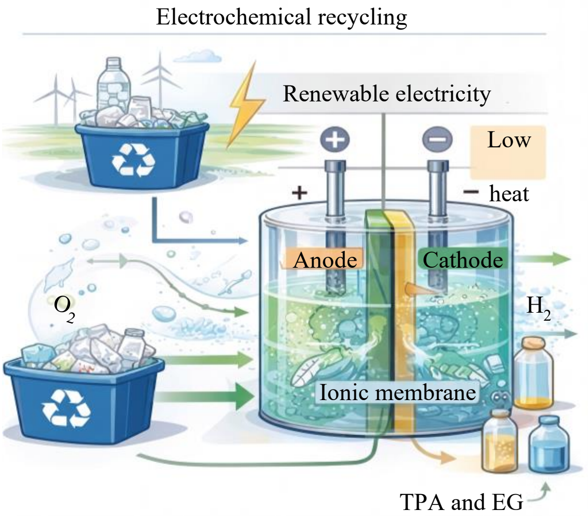

Figure 4. Schematic representation of electrochemical polymer depolymerization. In this, polymer chains undergo redox-driven bond cleavage in an electrochemical cell under mild operating conditions, producing monomers or value-added chemicals such as hydrogen and formate.

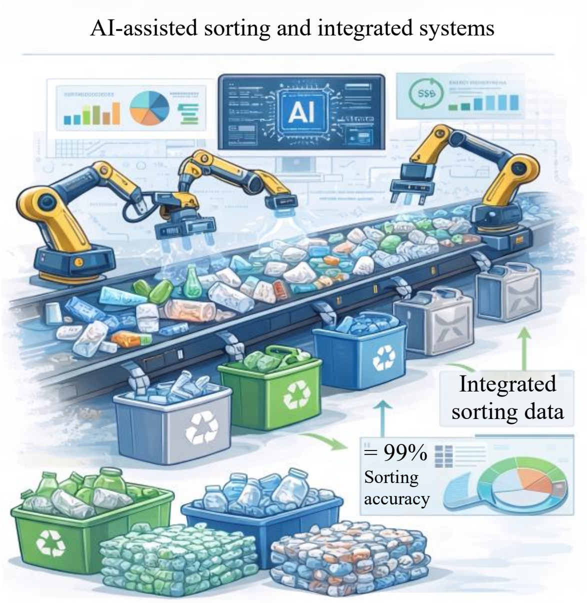

Figure 5. Schematic representation of AI-assisted sorting integrated within advanced recycling systems. In this, artificial intelligence-based systems employing computer vision, near-infrared (NIR) spectroscopy, and robotic separation enhance feedstock purity by identifying and segregating plastics according to polymer type. and color.

RESULTS AND DISCUSSIONS

Pyrolysis/gasification yields mostly fuels or syngas (0% monomer recovery for plastics), so their circularity is lower. Electrochemical approaches can selectively produce monomers or hydrogen with high faradaic efficiency, so their “monomer recovery” can be tailored. In terms of energy demand, enzymatic and electrochemical methods operate at low-to-moderate temperatures (≈50–80°C or room T) [10], implying lower heating energy. Solvolysis typically runs at 100–250°C (medium energy) and pyrolysis/gasification at 300–1200°C [10], requiring much more thermal energy. Feedstock flexibility varies: pyrolysis/gasification accepts mixed, contaminated waste easily, whereas enzymatic and solvolysis need relatively pure streams of specific polymers. AI sorting improves all methods by delivering cleaner feed [10].

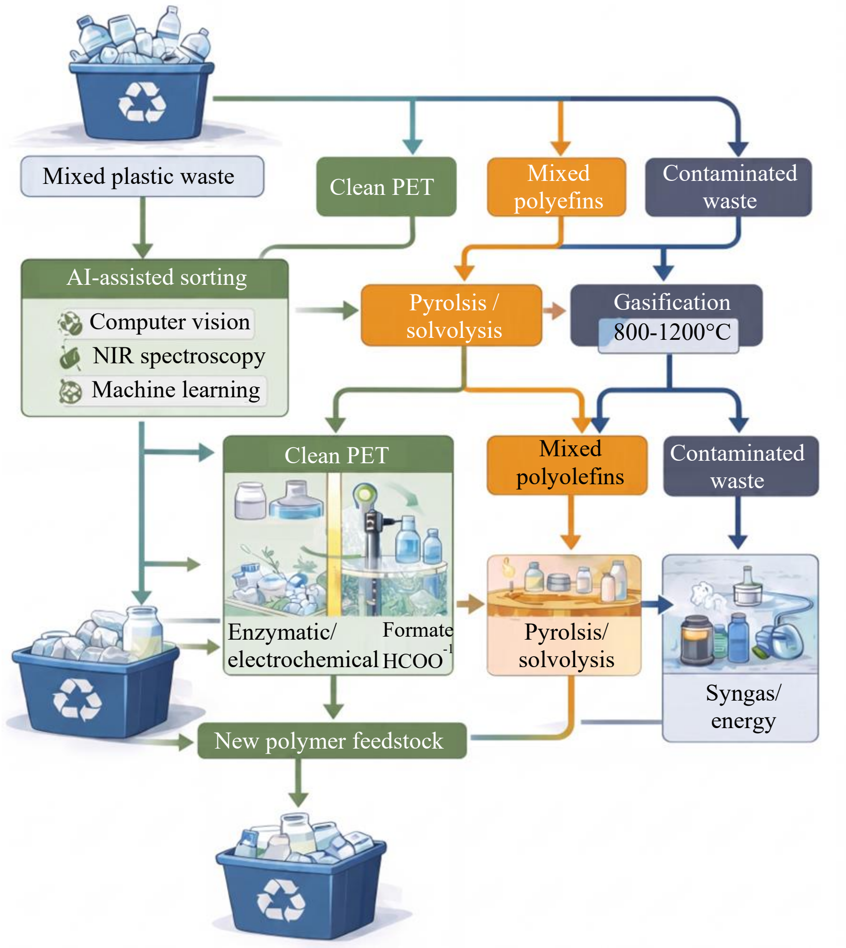

Figure 6. Integrated systems framework for next-generation polymer recycling, illustrating the allocation of plastic waste streams to appropriate recycling pathways.

Table 1 compares the major recycling methods on key criteria. Enzymatic recycling of PET achieves the highest monomer purity (close to 100%) and circularity. Glycolysis and other solvolytic routes also give near-virgin monomers (TPA yield ~85–95%) [10]. Economically, mature methods currently hold advantages. Mechanical and pyrolysis plants are already built at scale (TRL 7–9) [10], while enzymatic and electrochemical plants are mostly pilot or lab scale (TRL 5–7) [10]. Table 1 indicates approximate costs: chemical pyrolysis ~\$600–1000/t, enzymatic ~$500–900/t, and automated sorting ~$200–600/t. Enzymes and specialized reactors add capital, but fuel production in pyrolysis offsets some cost. Life-cycle studies suggest solvent-based and enzymatic recycling can halve GHG emissions relative to virgin plastics, while pyrolysis–gasification has higher emissions (unless waste heat or CCS is used). Importantly, hybrid systems outperform single approaches: for instance, sorted PET waste processed by enzymes achieves >90% circularity with modest energy, vs. unsorted waste incinerated or downcycled with ~10% efficiency [11, 9]. Table 1 shows that enzymatic and solvolysis processes can nearly close the material loop for PET, producing pure monomers for new polymers. Pyrolysis/gasification, by contrast, primarily converts plastic carbon into fuel, aiding resource recovery but not material circularity [10].

Critical Evaluation and Scalability Challenges:

Next-generation recycling technologies such as enzymatic and solvolytic depolymerization offer high monomer recovery and strong closed-loop potential, particularly for PET, but their scalability is limited by feedstock purity requirements, polymer specificity, reaction time, and cost.

Table 1. Comparison of major recycling methods.

Recycling Technology	**Primary Output**	**Circularity / Monomer Recovery**	**Operating Conditions / Energy Demand**	**Feedstock Tolerance**	**Recyclate Quality**	**Technology Readiness and Cost Trend**
Mechanical Recycling	Re-melted polymer pellets	Moderate (≈60–90%, decreases with cycles)	Low–moderate (shredding, washing, extrusion)	Requires clean, sorted thermoplastics; limited tolerance to additives	Downcycled polymer with degraded mechanical properties	High TRL (7–9); low cost (≈\$200–400 t^{-1}) but limited lifetime
Enzymatic Recycling (PET, polyesters)	Monomers (TPA, EG)	Very high (≈90–97%)	Low (≤65°C; aqueous systems)	Low polymer diversity but tolerant to dyes and additives	Virgin-equivalent monomers	Medium TRL (5–7); moderate cost (≈\$400–900 t^{-1}), improving rapidly
Solvolysis (Glycolysis, Methanolysis, Aminolysis)	Purified monomers/intermediates	Very high (≈80–95%)	Moderate (100–250°C; pressurized reactors)	Requires relatively pure, single-polymer streams	Near-virgin monomers after purification	Medium–high TRL; high capex, strong product value
Pyrolysis	Hydrocarbon oil, gas, char	Low (≈0% monomer recovery)	High (300–700°C)	Very high; accepts mixed and contaminated plastics	Fuel-grade oil (open-loop recycling)	High TRL; high capex (≈\$600–1000 t^{-1}), energy-intensive
Gasification	Syngas (CO + H_2)	Low (≈0% monomer recovery)	Very high (800–1200°C)	Very high; mixed waste streams	Energy/chemical feedstock	High TRL; very high capex and operating cost
Electrochemical Recycling	Monomers, H_2, formate, value chemicals	High (selective, tunable)	Low–moderate (ambient temperature, low voltage)	Moderate; requires milled or pretreated polymers	High-purity chemicals or monomers	Low–medium TRL; electricity cost and electrode stability critical
AI-Assisted Sorting (Enabling Technology)	High-purity plastic streams	— (indirect)	Low–moderate (sensor and robotic power)	Very high (≥95% polymer purity achievable)	Improves quality across all routes	Commercially emerging; capex intensive but cost-saving downstream

Thermochemical methods like pyrolysis and gasification are more industrially mature and can process mixed waste, yet they mainly produce fuels or basic chemicals rather than restoring original polymers, reducing material circularity and increasing energy demand. Electrochemical recycling presents a promising low-temperature, electricity-driven alternative but remains in early development with scale-up challenges. Therefore, an integrated approach combining AI-assisted sorting with targeted depolymerization and thermochemical treatment of residual streams is likely the most viable pathway toward a sustainable circular plastics economy.

CONCLUSION

Polymer recycling is getting better with technologies. These new ways of recycling can help us get resources back and make sure we use materials in a circle instead of just throwing them away. We can use helpers like enzymes to break down plastics into simple parts that we can use again. We can also use heat to break down plastics, which's good for big factories. Each way of recycling has its own problems. Some ways use a lot of energy, some are not very good at making circles with materials, some are not cheap. Some are not ready to be used yet. This study found that we cannot just use one way to recycle all the waste in the world. The plastic waste is too complicated and different. So we need to use a lot of ways together. We need to sort the plastics in a way, break them down into simple parts, use heat to break down the rest and use energy from renewable sources. This will help us find a solution that's fair and can be used by everyone. To make progress we need to make sure the technologies are good for the economy. We need to change the way we do things. We need to work together to make policies that help us get to a circular plastics economy that is good for the planet. Polymer recycling and the circular plastics economy are important for our future.

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