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Chemical Recycling of PET: Pathways, Process Bottlenecks, and Optimization Strategies - A Review

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ABSTRACT

Polyethylene terephthalate (PET) is one of the most produced plastics worldwide, yet less than 30% is effectively recycled, leading to significant environmental and economic challenges. This review critically evaluates major PET chemical recycling pathways hydrolysis, glycolysis, methanolysis, aminolysis, and enzymatic depolymerization focusing on reaction mechanisms, optimization strategies, and sustainability considerations. A structured literature survey (2010–2025) using Dimensions, Scopus, and Web of Science identified 95 relevant studies for comparative analysis. Results indicate that glycolysis provides the highest scalability with up to 95% bis(2-hydroxyethyl) terephthalate (BHET) yield, while hydrolysis offers >99% pure terephthalic acid (TPA) but requires high energy input. Methanolysis achieves >98% dimethyl terephthalate (DMT) purity under pressurized conditions, and enzymatic depolymerization operates at 30–70°C with approximately 85% selectivity, though limited by enzyme stability and cost. Hybrid chemo-enzymatic and AI-assisted approaches are emerging as promising solutions, potentially reducing energy demand by 20–30%. This review highlights that no single process fulfills all industrial criteria, emphasizing the need for catalyst innovation, reactor optimization, and integration of digital and biological strategies to achieve sustainable and economically viable PET recycling.

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1. INTRODUCTION

The global rise in plastic consumption has intensified interest in waste valorization the transformation of end-of-life materials into value-added products as a core strategy within the circular economy. Rather than viewing plastic waste solely as an environmental burden, waste valorization reframes it as a resource for chemical feedstocks, fuels, and advanced materials. This approach has gained momentum across academic, industrial, and policy sectors to reduce resource depletion, minimize landfill burden, and lower greenhouse gas emissions [1], [2]. Most PET waste is mechanically downcycled or incinerated, processes that either degrade material quality or contribute to CO_2 emissions. As a result, PET represents not only a pollutant of concern but also a technologically accessible target for high-value chemical recovery [3].

Polyethylene terephthalate (PET) is a widely used thermoplastic, primarily employed in packaging, textiles, and beverage bottles due to its durability, transparency, and cost-effectiveness. PET's high strength, barrier properties, and transparency have led to annual global production surpassing 50 million tons, yet recycling rates remain disappointingly low typically below 30% globally [4]. In the U.S., PET packaging accounted for up to 44.7% of single-serve containers by 2021 [5]. Given its non-biodegradable nature, improper

disposal of PET contributes to long-term pollution in landfills and aquatic systems [6]. To address these challenges, PET recycling has attracted policy and industrial attention as part of a global shift toward circular economy models. Recycling PET reduces reliance on fossil-derived raw materials, lowers greenhouse gas emissions, and supports compliance with emerging environmental policies such as the EU Circular Economy Action Plan and Extended Producer Responsibility (EPR) frameworks [7]. From an economic perspective, PET recycling can reduce the cost of raw materials and waste management especially when closed-loop processes are used to produce near-virgin PET from post-consumer sources [8].

Four main recycling routes are currently applied to PET: mechanical, chemical, enzymatic, and pyrolytic. Among these, chemical recycling offers the most potential to valorize PET by breaking it down into high-purity monomers such as terephthalic acid (TPA) and ethylene glycol (EG). This is particularly crucial for contaminated or mixed plastic streams where mechanical recycling is ineffective. Chemical depolymerization enables the re-synthesis of virgin-grade PET, making it suitable for food-contact applications and high-performance materials [9]. This shift is further accelerated by growing regulatory and societal pressure. Governments are implementing stricter packaging laws, mandating recycled content, and offering incentives for innovation in recycling infrastructure. As a result, chemical recycling is emerging as a vital complement to mechanical processing, especially for colored, multilayered, or otherwise non-recyclable PET [1].

This review critically examines the main chemical depolymerization pathways for PET: hydrolysis, glycolysis, methanolysis, aminolysis, and hybrid processes. Hydrolysis enables depolymerization under aqueous conditions, often with non-toxic solvents and moderate temperatures [6]. Glycolysis is currently the most industrially advanced route, offering rapid reaction rates and relatively mild conditions [10]. Methanolysis and aminolysis, though less common at scale, show promise for their selective recovery and product versatility [11]. Finally, hybrid and integrated approaches that combine depolymerization techniques or introduce catalytic innovations may offer superior yields, energy savings, and process intensification [8].

Although several reviews have covered PET chemical recycling, few have systematically examined process optimization strategies including catalytic innovation, reactor engineering, and sustainability assessment across multiple depolymerization pathways. Most existing reviews emphasize reaction mechanisms or catalyst types but lack a comparative evaluation of energy performance, product yield, and economic feasibility. This paper addresses that gap by critically analyzing chemical recycling pathways in terms of their operational efficiency, scalability, and sustainability.

The novelty of this review lies in its integration of process optimization, techno-economic analysis, and sustainability perspectives into a unified framework, providing actionable insights for both academic research and industrial application. To guide this review, four key questions are addressed each corresponding to a major analytical section of the paper:

1. What are the current chemical depolymerization pathways for PET, and how do they operate in terms of mechanisms, conditions, and catalytic systems?
2. How do these recycling methods compare in terms of monomer yield, product purity, scalability, and environmental performance?
3. What recent strategies such as advanced catalysis, reactor engineering, and integrated processes have improved the efficiency and feasibility of PET depolymerization?
4. What do current techno-economic and life cycle assessments reveal about the sustainability and industrial viability of these chemical recycling technologies?

1.1. Fundamentals of PET Chemistry and Recycling Challenges

Polyethylene terephthalate (PET) is a thermoplastic polyester widely used in packaging, textiles, and engineering applications due to its excellent mechanical strength, chemical resistance, transparency, and barrier properties. Structurally, PET is composed of repeating units of ethylene glycol (EG) and terephthalic acid (TPA), connected via ester bonds that form a linear, semi-crystalline polymer chain. This ester linkage is the primary target in chemical depolymerization processes, where hydrolysis, glycolysis, or methanolysis reactions cleave the backbone into reusable monomers [12]. PET's degree of crystallinity (typically 30–50%) plays a major role in its processability and recyclability. Crystalline regions are more resistant to chemical attack and thermal degradation, whereas amorphous regions allow easier access for solvents or enzymes during depolymerization. Additionally, during product manufacturing or recycling, PET can undergo thermal and hydrolytic degradation, resulting in reduced molecular weight and changes in viscosity and color [13].

Another critical consideration is the presence of additives, colorants, and multilayer components in post-consumer PET waste. These include stabilizers, UV absorbers, and fluorescent tracers used for sorting enhancement. While such additives improve material performance or logistics, they can complicate chemical recycling by interfering with catalyst activity, lowering monomer yield, or requiring additional purification

steps [14]. In particular, the challenge of efficiently processing blended or contaminated PET waste is one of the key limitations in scaling chemical recycling technologies. Table 1 presents the key physical and chemical properties of PET that are most relevant to its recycling process.

Table 1. Key physical and chemical properties of PET relevant to recycling

Property	Typical Value	Reference
Glass Transition Temperature (Tg)	75–80°C	[12]
Melting Temperature (Tm)	250–260°C	[13]
Crystallinity	30–50% (dependent on history)	[15]
Density	1.37–1.40 g/cm³	[12]
Ester Bond Density	~7.3 mmol/g	[16]
Common Additives	TiO_2, dyes, UV stabilizers	[14]

1.2. Mechanisms of PET Depolymerization

The chemical recycling of PET is fundamentally based on depolymerization, where the polymer backbone is cleaved to recover its original monomers or valuable intermediates. These reactions target the ester linkages between the terephthalic acid (TPA) and ethylene glycol (EG) units in PET. Several depolymerization routes have been developed, each following distinct chemical mechanisms and requiring specific conditions, solvents, and catalysts (see Fig. 1).

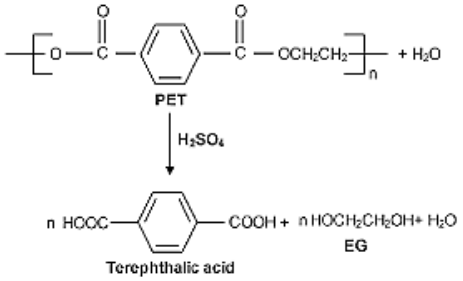

Fig. 1. Mechanisms of PET depolymerization

In hydrolysis, PET is treated with water under acidic, alkaline, or neutral conditions. Alkaline hydrolysis typically involves sodium hydroxide, breaking the ester bonds to yield sodium terephthalate and EG. Acidic hydrolysis, often using sulfuric acid, yields free TPA and EG. The general mechanism involves nucleophilic attack by water or hydroxide ions on the carbonyl carbon of the ester bond, leading to bond cleavage and release of monomers [6].

Glycolysis involves the transesterification of PET using excess ethylene glycol (or other glycols), producing bis(2-hydroxyethyl) terephthalate (BHET) as the main product. The ester bond in PET is cleaved and replaced with glycol end groups. Catalysts such as metal acetates, ionic liquids, or metal oxides accelerate this equilibrium-limited reaction by enhancing the electrophilicity of the carbonyl carbon [8].

Methanolysis is similar in principle but uses methanol to produce dimethyl terephthalate (DMT) and EG. This process generally requires pressurized conditions (20–30 bar) and elevated temperatures (180–280°C) due to methanol's lower reactivity. Like glycolysis, methanolysis proceeds through nucleophilic substitution at the ester bond, often catalyzed by metal salts or organometallic complexes [7].

Aminolysis uses primary or secondary amines (e.g., ethanolamine, hydrazine) to form terephthalamide derivatives. The mechanism involves nucleophilic attack by the amine, yielding mono- or bis-amide products, often under milder conditions than alcohol-based depolymerization. This pathway is especially promising for producing functional intermediates for resins or curing agents [17].

In enzymatic depolymerization, enzymes such as PETase and MHETase catalyze the hydrolysis of PET under mild, aqueous conditions. The reaction proceeds through surface erosion, where ester bonds are cleaved at the polymer–enzyme interface, generating MHET, TPA, and EG. This process offers high selectivity and low energy demand, although current challenges include enzyme stability, rate, and substrate specificity [18].

2. METHODOLOGY

The analysis followed a structured approach beginning with defining the review scope and research questions, followed by a multi-database literature search (Dimensions, Scopus, Web of Science; 2010–2025). After screening 220 publications, 95 articles were selected for detailed analysis based on inclusion criteria.

Data were extracted on reaction pathways, catalysts, yields, scalability, and sustainability indicators, enabling a comparative evaluation of chemical recycling methods and the identification of optimization strategies and future research directions. The overall process followed in conducting this review from defining the research scope to synthesizing optimization insights is illustrated in Fig. 2.

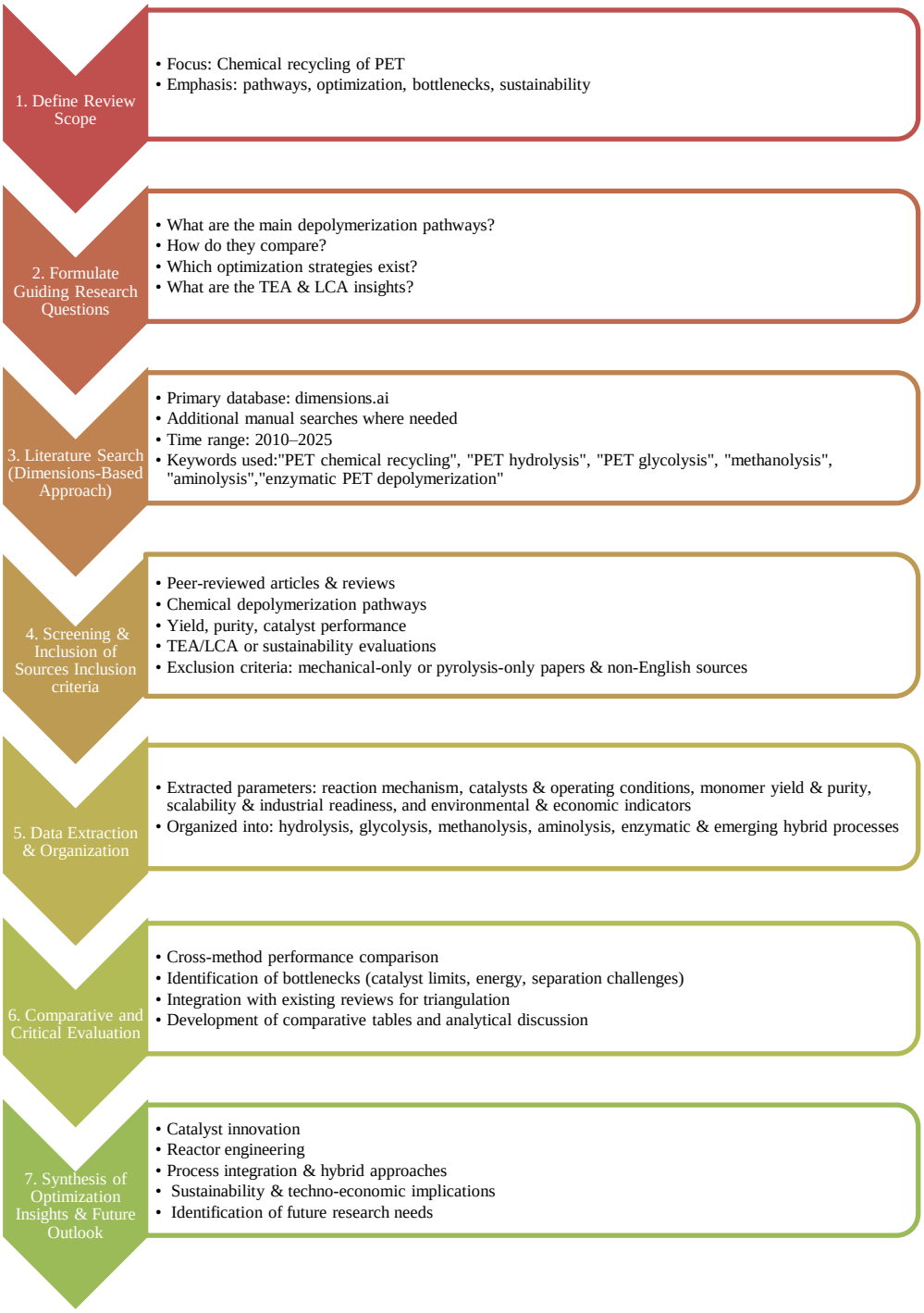

Fig. 2. Methodology

3. RESULTS AND DISCUSSION

3.1. Chemical Recycling Pathways for PET

3.1.1. Hydrolysis (Alkaline, Acidic, Neutral)

Hydrolysis of PET involves cleaving the ester bonds in the polymer backbone using water, typically under elevated temperature and pressure. It is classified into three types alkaline, acidic, and neutral hydrolysis each with distinct operating conditions, catalysts, and environmental profiles.

Alkaline hydrolysis, often using NaOH or KOH, is one of the most widely studied and effective methods for PET depolymerization. It typically operates at 100–250°C and ambient to high pressure. This method yields terephthalic acid (TPA) and ethylene glycol (EG), but requires neutralization of the basic medium post-reaction, generating salt waste [19]. Zinc acetate, a widely used catalyst, has been shown to significantly increase hydrolysis rates and reduce energy input requirements (Kilanko & Olamigoke, 2024).

Acidic hydrolysis involves strong mineral acids (commonly sulfuric acid), which also achieve complete depolymerization of PET, even under milder temperatures than alkaline hydrolysis. However, the corrosive environment and challenges in acid recovery limit its industrial scalability [21].

Neutral hydrolysis is gaining attention due to its greener profile avoiding corrosive or toxic byproducts. This reaction usually requires higher temperatures (200–300°C) and longer reaction times due to the absence of catalysts, making it less energy-efficient. However, the use of cosolvents like ethylene glycol and optimized solid–liquid ratios can improve yield and product purity [22]. Some studies show successful catalyst-free depolymerization with high TPA purity, favoring industrial application if heat integration is optimized [2].

Mechanistically, hydrolysis proceeds via nucleophilic attack on the ester carbonyl carbon, facilitated by hydroxide ions (in alkaline) or hydronium ions (in acidic). Recent catalyst developments include ionic liquids, eutectic solvents, and metal–organic frameworks (MOFs), which enhance depolymerization rates while maintaining product selectivity [19], [23]. These innovations aim to lower energy demands, improve scalability, and enable process integration with hybrid or multi-step recycling systems.

3.1.2. Glycolysis

Common glycols, temperatures, reaction time

Glycolysis is one of the most established and scalable chemical recycling routes for PET. It involves depolymerizing PET using glycols primarily ethylene glycol (EG) to yield bis(2-hydroxyethyl) terephthalate (BHET), which can be reused for PET synthesis. Other glycols, like diethylene glycol and propylene glycol, are also explored for tuning polymer reactivity or downstream properties [24]. Typical reaction temperatures range from 180–250°C, and reaction times vary between 30 minutes to 2 hours, depending on the catalyst and glycol type. Fast depolymerization with complete conversion has been demonstrated in as little as 72 minutes under optimized conditions using organocatalysts [25].

Role of metal and organocatalysts

Catalysts play a critical role in reducing energy demands and improving product selectivity. Metal-based catalysts, such as zinc acetate, manganese acetate, and cobalt salts, have long been used for industrial-scale glycolysis due to their high activity and cost-efficiency. However, organocatalysts are gaining attention for their low toxicity, recyclability, and potential to enable greener processing. For example, heterogeneous silica-supported organocatalysts such as Si-TEA and triazabicyclodecene (TBD)-modified silica have shown high monomer yields across multiple reuse cycles, making them promising for continuous processes [26]. Additionally, ionic organocatalysts, like DBU/pTSA or 1,3-dimethylimidazolium-2-carboxylate, provide fast PET conversion at moderate temperatures and demonstrate tunable selectivity through structural modifications [27], [28]. Advanced systems also show promise for handling colored or multi-layered PET waste, with high BHET conversion rates (~93%) and metal recovery from complex materials like payment cards [29]. These developments point toward a growing ability to tailor catalysts based on feedstock type, desired product profile, and environmental compatibility, aligning glycolysis with circular economy goals.

3.1.3. Methanolysis

Pressurized systems, co-solvent use, reactor design

Methanolysis involves depolymerizing PET with methanol to yield dimethyl terephthalate (DMT) and ethylene glycol (EG) both valuable monomers for virgin PET synthesis. This method is especially effective for contaminated or colored PET, making it suitable for complex post-consumer waste streams [8]. Methanolysis typically requires pressurized systems due to the need to keep methanol in the liquid phase at elevated temperatures. Operating conditions often involve temperatures of 180–280°C and pressures up to 2–4 MPa, depending on the catalyst and reactor configuration. Reactor design plays a critical role in scalability. Recent advances include tubular flow reactors and high-pressure stirred-tank reactors that offer better mass transfer and temperature control. Additionally, integrated methanol recovery systems improve solvent reuse and reduce operational costs [5]. The use of co-solvents, such as ethanol or ethylene glycol, has also been investigated to

reduce methanol requirements, improve solubility of intermediates, or facilitate product separation. These systems can lower energy input or expand the compatibility with multi-material waste streams [31]. While methanolysis is less commercially mature than glycolysis, it remains promising due to the high quality of its products and compatibility with mixed-waste inputs—especially when integrated with circular economy strategies [32].

3.1.4. Aminolysis and Enzymatic Alternatives

Emerging pathways with niche applications

Aminolysis, involving the reaction of PET with amines (e.g., ethanolamine, hydrazine), is a selective depolymerization route that produces terephthalamide derivatives. These products have value in producing resins, curing agents, and functional additives, giving aminolysis niche potential in high-value chemical upcycling [33]. It operates under relatively mild conditions (100–180°C) and can be catalyzed by bases or proceed uncatalyzed in excess amine solvents. Meanwhile, enzymatic recycling is gaining significant interest as a low-energy, environmentally friendly route, especially suited for mixed or colored PET waste. Enzymes such as PETase and MHETase have shown potential for degrading PET into its monomers under ambient to moderate temperatures. These biocatalytic methods offer high substrate specificity and selectivity, avoiding the formation of undesirable side-products [34].

Selectivity, toxicity, and downstream purification

Aminolysis generally exhibits high selectivity toward amide products, but its limitations include toxic amine reagents and the generation of non-volatile byproducts that complicate downstream purification. Post-reaction steps often require extraction, crystallization, or chromatography for isolation of the desired terephthalamide products [35]. Enzymatic approaches, by contrast, offer low-toxicity and biodegradable reaction systems. However, they currently face challenges including slow kinetics, enzyme stability, and scalability at industrial levels [7]. Nevertheless, integration with microbial bioconversion platforms allows for downstream transformation of PET-derived monomers into value-added biochemicals such as vanillin, catechol, or adipic acid [18]. Despite their limitations, both aminolysis and enzymatic recycling hold promise as complementary approaches to mainstream chemical recycling, particularly in specialized applications or for advancing closed-loop textile and packaging systems [36].

The comparative reaction pathways of PET chemical depolymerization are summarized in Table 2, highlighting distinct operating conditions, catalysts, and conversion efficiencies. Hydrolysis and glycolysis remain the most mature routes, achieving monomer yields above 90%, while enzymatic depolymerization offers lower-temperature operation with moderate conversion efficiency but significant sustainability advantages. Methanolysis and aminolysis provide product flexibility, though their industrial scalability remains limited due to energy and purification constraints.

Table 2. Overview of PET chemical depolymerization pathways

Depolymeri-zation Route	Reaction Conditions	Catalysts/ Agents	Main Products	Typical Yields (%)	Advantages	Limitations
Hydrolysis	200–250°C, 1–4 MPa	NaOH, H_2SO_4, water	Terephthalic acid (TPA), Ethylene glycol (EG)	90–99	Produces pure TPA; suitable for food-grade PET	High energy input; corrosion; wastewater treatment required
Glycolysis	180–220°C, atm. pressure	$Zn(OAc)_2$, $Mn(OAc)_2$	Bis(2-hydroxyethyl) terephthalate (BHET)	85–95	Mild conditions; scalable; closed-loop PET synthesis	Requires BHET purification; catalyst reuse issues
Methanolysis	180–280°C, 2–4 MPa	Zn, Co acetate	Dimethyl terephthalate (DMT), EG	85–98	High product purity; compatible with colored PET	High pressure; solvent recovery needed
Aminolysis	100–180°C	$AlCl_3$, ethylenediamine	Terephthalamides	70–85	Produces functionalized monomers	Limited industrial use; purification challenges
Enzymatic Depolymerization	30–70°C	PET hydrolases (e.g., LCC, Cutinase)	TPA, EG	60–85	Green process; high selectivity	Slow kinetics; enzyme cost; crystallinity sensitivity

3.2. Comparative Analysis of PET Chemical Recycling Methods

A comparative evaluation of hydrolysis, glycolysis, methanolysis, and aminolysis/enzymatic depolymerization reveals trade-offs in monomer yield, purity, scalability, environmental footprint, and process economics. While each method holds specific advantages, their suitability depends on waste type, desired end-products, and integration potential with circular economy models. Table 3 provides a comparative overview of the major chemical recycling methods for PET.

Table 3. Comparative overview of PET chemical recycling methods

Method	Monomer Yield	Monomer Purity	Scalability	Environmental Impact	Economic Feasibility
Hydrolysis	High (especially alkaline) [2]	High (TPA, EG)	Moderate (corrosion issues in acidic)	Salt waste (alkaline); high water use [19]	Moderate; neutral hydrolysis shows potential [38]
Glycolysis	High (80–95% BHET) [26]	Moderate to High	High (most industrialized)	Moderate; EG is recyclable [25]	High; mature catalysts and lower pressure
Methanolysis	High (85–95% DMT, EG)	Very High [8]	Limited (requires pressure vessels)	Moderate to high; solvent recovery required [39]	Moderate; costly reactor design and methanol use
Aminolysis	Variable (60–90%) [33]	Intermediate	Low; niche applications	Moderate to high toxicity (amines) [35]	Low; high cost of amines and purification
Enzymatic	Lower (~30–60%) [18]	Very High	Currently low; emerging	Excellent (biodegradable, low energy) [7]	Low to moderate; enzyme production is costly

Across the reviewed depolymerization routes, the balance between yield, purity, and operational severity strongly determines process feasibility. Glycolysis typically achieves up to 95% bis(2-hydroxyethyl) terephthalate (BHET) yield under moderate conditions (180–220°C) using zinc acetate or manganese acetate catalysts, making it the most scalable process at industrial scale [9]. Hydrolysis, on the other hand, can deliver >99% pure terephthalic acid (TPA) with high selectivity, although its dependence on elevated temperature and corrosive environments increases both energy consumption and equipment cost [37].

Methanolysis provides 85–95% dimethyl terephthalate (DMT) yield under pressures of 2–4 MPa, resulting in a monomer purity above 98%, but requires solvent recovery systems and pressurized operation [40]. Aminolysis demonstrates 70–85% conversion efficiency, producing terephthalamides that are valuable for specialty polymer synthesis yet constrained by complex purification needs. Meanwhile, enzymatic depolymerization operates at 30–70°C with 60–85% monomer selectivity, offering a low-energy alternative suitable for contaminated or colored PET, though limited by enzyme stability and crystallinity effects [41].

Nevertheless, each pathway presents unique trade-offs: hydrolysis and methanolysis ensure high product purity but entail higher energy costs, whereas glycolysis and enzymatic depolymerization offer flexibility and lower environmental impact at the expense of reaction time or product refinement. Future improvements should therefore focus on hybrid processes for instance, integrating glycolysis pretreatment with enzymatic depolymerization to combine operational efficiency with green chemistry advantages. [42].

3.3. Process Optimization

Enhancing the efficiency and sustainability of PET chemical recycling has become a central focus in recent research, with innovations targeting catalysis, reactor design, and system integration. Catalytic advancements, particularly involving ionic liquids (ILs), metal oxides, and metal–organic frameworks (MOFs), have shown significant promise. ILs offer tunable acidity, low volatility, and recyclability, improving depolymerization rates and product selectivity [4]. MOFs, owing to their high surface area and structural flexibility, have emerged as robust heterogeneous catalysts with potential for selective PET depolymerization [43]. Metal oxides like ZnO and MnO_2 are also used to reduce activation energies in glycolysis and methanolysis, enabling lower operating temperatures and shorter reaction times.

Beyond catalysis, reactor design plays a crucial role in process efficiency. Microwave-assisted systems allow for rapid, uniform heating, reducing reaction times and energy consumption, particularly in glycolysis and hydrolysis. Meanwhile, continuous-flow reactors are gaining traction for their scalability, improved thermal control, and compatibility with catalyst recycling [44]. These flow systems are particularly advantageous in enabling in-line product separation and real-time monitoring, critical for industrial integration.

Efforts are also underway to integrate depolymerization with repolymerization or biological upcycling, forming closed-loop recycling systems. For instance, BHET obtained from glycolysis can be directly used in the re-synthesis of PET without extensive purification. In enzymatic processes, monomers like terephthalic acid and ethylene glycol can be further transformed by engineered microbes into high-value products such as vanillin or biopolymers [4]. These hybrid and modular systems offer the potential to maximize resource efficiency, reduce environmental footprint, and unlock new economic value from PET waste. Collectively, such strategies represent a crucial evolution from isolated recycling steps toward integrated, smart recycling platforms that align with future industrial and environmental goals.Labels: Use 10 point Times New Roman for Figure labels. Use words rather than symbols or abbreviations when writing Figure axis labels to avoid confusing the reader. As an example, write the quantity "Magnetization," or "Magnetization, M," not just "M." If including units in the label, present them within parentheses. Do not label axes only with units. In the example, write "Magnetization (A/m)" or "Magnetization (A (m(1)," not just "A/m." Do not label axes with a ratio of quantities and units. For example, write "Temperature (K)," not "Temperature/K."

3.4. Techno-economic and Sustainability Considerations

Techno-economic and life cycle assessments (TEA and LCA) have become essential tools for evaluating the real-world viability of PET chemical recycling. These analyses provide insights into environmental performance, energy demand, and economic trade-offs compared to both mechanical recycling and virgin PET production. Recent LCA studies show that enzymatic depolymerization offers a substantial reduction in environmental footprint, with energy savings of up to 83% and greenhouse gas emission reductions of 17–43%, especially when enzymatic monomers are upcycled into higher-value products [45]. Similarly, fully integrated chemical recycling systems for PET-G blends have demonstrated a 67% reduction in global warming potential, though they come with 69% higher annualized costs due to more complex process configurations [46].

When comparing individual pathways, methanolysis is often favored for its ability to produce high-purity monomers with relatively low environmental impact, especially in scenarios involving mixed polyester waste. A comparative TEA showed that methanolysis had lower impact scores in categories such as acidification and carcinogenicity, due in part to its more efficient separation and purification routes [47]. Glycolysis, on the other hand, is more energy-intensive than enzymatic recycling but remains cost-effective due to its mature catalyst systems, milder pressure requirements, and commercial readiness [48].

Trade-offs are evident in balancing cost vs. purity and scale vs. control. High-purity monomer recovery via enzymatic or methanolysis processes often requires complex separation steps or high-cost inputs (e.g., enzymes, methanol), limiting economic scalability. Conversely, scalable systems like glycolysis in continuous reactors offer lower monomer purity but are easier to implement at industrial scale. Energy input is another key variable: while enzymatic processes operate under mild conditions, their slower kinetics may reduce throughput, and their economic success hinges on reducing enzyme production costs.

Ultimately, the feasibility of PET chemical recycling is highly context-dependent, shaped by feedstock composition, energy source, policy incentives, and product value. To enable broader adoption, future research must combine process optimization with robust TEA/LCA frameworks that guide decision-making across scientific, industrial, and policy domains.

4. CHALLENGES AND FUTURE OUTLOOK

Despite rapid advancements, PET chemical recycling continues to face significant technical and practical challenges that limit its full-scale deployment. One major issue is catalyst deactivation, often caused by thermal degradation, residue accumulation, or loss of active sites particularly in solvent-intensive processes. These effects reduce reaction efficiency and require frequent catalyst regeneration or replacement [49]. Additionally, product purification especially from methanolysis or aminolysis routes remains costly and energy-intensive due to the presence of solvents, dyes, and additives in real PET waste streams [46]. In enzymatic recycling, the stability and lifetime of PET-degrading enzymes under industrial conditions are still poorly understood, limiting their economic competitiveness [45].

A prominent gap in current research is the limited testing on real-world, mixed-plastic feedstocks. Most studies still rely on clean, single-type PET inputs, which does not reflect the heterogeneity of post-consumer waste. This hinders the practical applicability of lab-scale results to commercial environments [47]. Moreover, the integration of chemical depolymerization with downstream repolymerization or upcycling remains fragmented, with few examples demonstrating fully closed-loop systems under continuous operation.

Looking ahead, emerging research directions include hybrid chemical-biological processes, where PET-derived monomers are further converted by engineered microbes into high-value compounds like vanillin,

catechol, or biodegradable polyesters [50]. Another promising area is the use of digital modeling and AI-driven optimization, which enables rapid catalyst screening, process simulation, and energy forecasting reducing trial-and-error in experimental design. Novel concepts like solvent-free aerobic depolymerization have also shown potential to simplify operations and minimize waste by enabling high-yield monomer recovery without downstream separation steps [49]. Additionally, photocatalytic PET reforming for simultaneous hydrogen generation and plastic degradation is under early exploration as a dual-purpose, low-carbon technology [51].

In summary, overcoming the technical bottlenecks and scaling limitations of PET chemical recycling will require collaborative, interdisciplinary approaches that integrate advances in catalysis, process engineering, materials science, and digital technologies. These efforts are essential to develop robust, economically viable recycling systems that align with long-term sustainability and circular economy goals.

5. CONCLUSION

Chemical recycling of polyethylene terephthalate (PET) remains one of the most viable approaches for achieving a circular plastics economy. Among the analyzed pathways, glycolysis demonstrated the highest industrial readiness with up to 95% bis(2-hydroxyethyl) terephthalate (BHET) yield, moderate energy requirements, and compatibility with closed-loop PET synthesis. Hydrolysis provided >99% pure terephthalic acid (TPA), making it ideal for food-grade applications, although its high energy and chemical demands limit scalability. Methanolysis achieved 85–95% dimethsyl terephthalate (DMT) purity but requires complex solvent recovery, while enzymatic depolymerization showed strong potential for low-temperature operation (30–70°C) and high selectivity (≈85%), pending advances in enzyme stability and kinetics. From a sustainability standpoint, all chemical routes outperform virgin PET synthesis in carbon and energy footprints, yet optimization is required in catalyst recovery, energy input, and product purification. Industrial progress will depend on the integration of hybrid chemo-enzymatic systems, machine learning–assisted process modeling, and techno-economic coupling of depolymerization and repolymerization steps. Future research should focus on (i) AI-driven optimization to identify ideal reaction windows and catalyst configurations, (ii) enzyme engineering for improved depolymerization rates, and (iii) circular reactor design enabling continuous, energy-efficient PET upcycling. Strengthening these aspects will accelerate the transition from laboratory-scale demonstration to sustainable industrial implementation.

Author Contribution

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The authors declare no conflict of interest.

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