

Review

Recent Progress in Polyamide Recycling for Sustainable Circular Economy

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Abstract

Polyamide (PA) is widely used as a high-performance engineering thermoplastic in automotive components and textiles, due to its superior mechanical strength and chemical resistance. However, the increase in PA waste has posed significant challenges to resource sustainability and environmental protection. Despite breakthrough development achieved in PA recycling, key barriers remain in process scale-up and high-value recovery. This review examines the current state of PA recycling, analyzing the research prospects of mechanical and chemical recycling from economic feasibility and environmental impact. We present discussions on innovative recycling approaches for PA, including upcycling, molecular design of novel PA derivatives, chemo-biological coupling and solvent-based recovery, offering potential solutions to the sustainable circular economy and green cycles. Finally, by presenting case studies, we highlight pathways toward future innovation that inform industrial-scale implementation.

Keywords: polyamide waste; mechanical recycling; chemical recycling; innovative recycling; circular economy



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1. Introduction

Plastics have become indispensable in modern life and industry owing to their versatile and advantageous properties. Global plastic production reached 460 million tons in 2019 and is projected to increase to 1.23 billion tons by 2060. However, only about 9% of global plastic waste was recycled in 2019, markedly lower than the 50% landfilled or 18% incinerated, making it the least utilized of the major waste management pathways [1]. Landfilling occupies extensive land area and can cause severe contamination of soil and groundwater, while incineration releases large amounts of toxic gases, posing substantial risks to environmental and human health. Microplastics and nanoplastics originate from the breakdown of larger plastics and industrial emissions. They can enter the human body via inhalation or dermal contact and are associated with potential health issues including DNA damage. Furthermore, they accumulate in ecosystems, endangering food safety. The

continuous increase in plastic production is intensifying these environmental and health threats [2].

Polyamide (PA) is one of the five major engineering plastics and occupies a prominent position in polymer science and industry [3]. PA is characterized by high mechanical strength, excellent impact resistance, and good reinforcement capabilities. These properties underpin their extensive use in diverse sectors, including electronics, automotive components [4,5], food packaging, and textiles. Figure 1 presents the sources of PA products, the corresponding recycling methods for the resulting waste, and the comparative environmental impact associated with each recycling pathway. Current global annual consumption of PA exceeds 8 million metric tons and continues to grow steadily at approximately 2.2% per annum. The market is projected to reach 10.4 million metric tons valued at around US\$47 billion by 2027 [6]. PA6 and PA66 dominate global PA production, with annual productions of about 5 million and 2.5 million metric tons. However, the combination of high demand and relatively short service lives leads to the accumulation of substantial PA waste [7,8]. Furthermore, PA is inherently resistant to natural degradation [9]. Consequently, waste streams containing PA are frequently incinerated for energy recovery or sent to landfills. This practice results in considerable resource loss and environmental pollution [10–12].

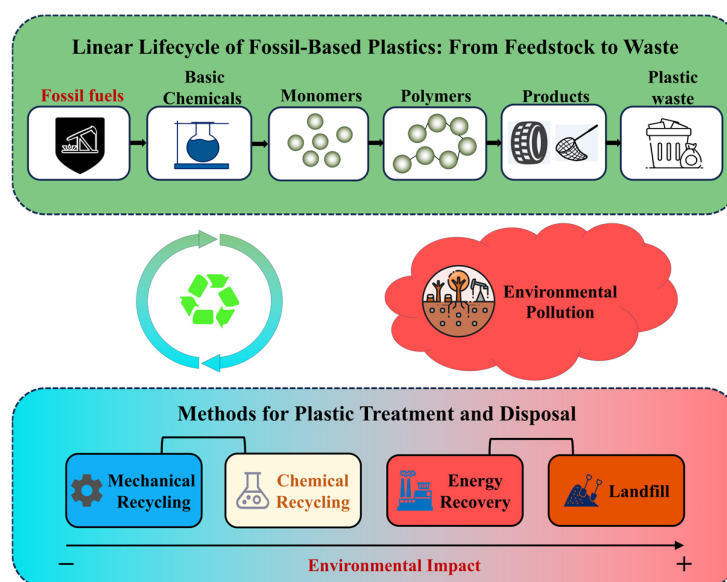


Figure 1. Schematic Diagram of Environmental Impacts from Plastic Full Life Cycle Processes and Waste Disposal Pathways.

Current PA recycling primarily relies on mechanical and chemical methods. Mechanical recycling offers advantages including operational simplicity and a relatively low environmental footprint. As a technologically mature process, it is widely adopted for recovering PA waste. However, it inevitably faces challenges such as molecular weight reduction and property deterioration over multiple cycles, and its long-term reliability requires further evaluation and optimization. Moreover, chemical recycling of PA has been implemented at an industrial scale only in some developed economies [13,14]. For instance, Germany's Zimmer AG pioneered a PA-6 acid depolymerization line with an annual capacity of 20,000 t. BASF has developed a multi-process parallel recycling system. Its operational assets comprise an integrated acid- and base-catalyzed PA-6 depolymerization line (20,000 t/a) and a PA-66 alkaline depolymerization line (24,000 t/a). DuPont has focused on alcoholysis, successfully commissioning a methanol alcoholysis line for PA-66 with a capacity of 230 t/a. This provides a differentiated technological pathway for its green recycling [15–17]. A major constraint for chemical recycling is that it typically requires

harsh conditions or the use of potent chemical reagents. Consequently, the development of efficient, cost-effective, and environmentally benign closed-loop recycling technologies for PA represents an urgent scientific and industrial imperative to enable their sustainable utilization.

Figure 2 presents a keyword co-occurrence network analysis for the field of plastic recycling. The study utilizes bibliometric analysis to systematically quantify and contextualize the academic literature on PA recycling. By synthesizing historical research, this approach delineates key trajectories in the evolution of knowledge within the field. This network visualization reveals that recent research on PA recycling is strongly centered on chemical recycling. The field encompasses several key technical branches: solvent-based recovery (e.g., selective dissolution), depolymerization (including enzymatic pathways), and upcycling. Notably, enzymatic depolymerization forms a conceptual bridge to the broader biological recycling pathway. In contrast to the diverse landscape of chemical recycling, research on PA mechanical recycling has been more limited. Recent work in this area has primarily addressed the recycling of mixed plastics, particularly blends containing PA, polypropylene (PP), and high-density polyethylene (HDPE). Fundamentally, PA recycling is anchored in the principles of the circular economy and sustainability. The network analysis further highlights key developmental needs, particularly the optimization of solvent greenness and the reduction in process energy consumption.

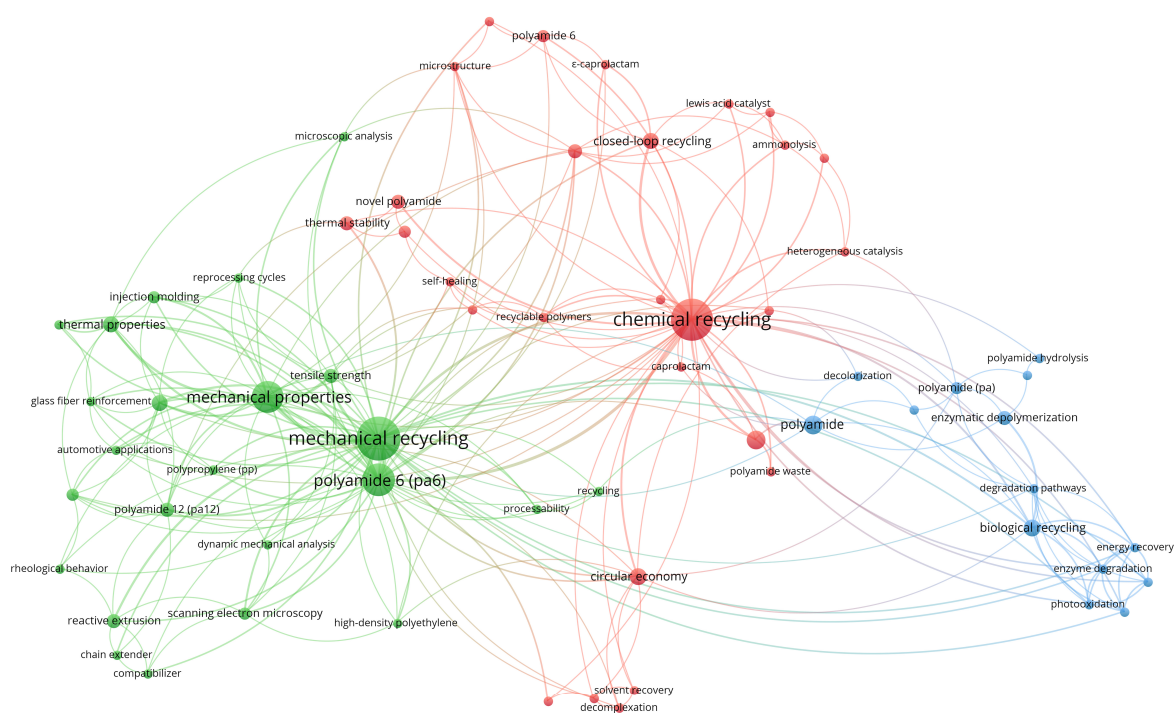


Figure 2. Research Network Diagram for PA Recycling and Plastic Circularity, utilizing different colors to distinguish clusters.

Hirschberg et al. [6] analyze the advantages, disadvantages, and applicability of PA recycling methods from both economic and technical perspectives. This work provides a valuable reference for selecting recycling pathways, but it does not explore the core mechanisms linking recycling with degradation, or their relationship to PA synthesis. Based on this, Zheng et al. [11] elucidated the core mechanisms linking PA synthesis and recycling. Novel PA recycling technologies are crucial to improving practicality and overcoming the limitations of traditional methods. However, the integration and scaling of these innovative approaches remain inadequate. This review provides a systematic summary of the indus-

trial status, technical bottlenecks, and development trends in mechanical and chemical PA recycling, with a focus on advancements in conventional methods and breakthroughs in emerging technologies. Furthermore, it provides a systematic discussion of innovative recycling paradigms, including upcycling, molecular design, biochemical coupling, and solvent recovery. Therefore, this work addresses key research gaps, specifically the limited comprehensive coverage of innovative technologies and the lack of holistic process integration, providing enhanced theoretical support and practical guidance for achieving a closed-loop PA economy.

2. Mechanical Recycling

Mechanical recycling is a physical recovery process that converts plastic waste into secondary raw material without altering its chemical structure. The standard procedure comprises sequential steps: sorting, crushing, washing, drying, and melt extrusion palletization, yielding recycled plastic pellets suitable for manufacturing new products. Due to its applicability to thermoplastics and the absence of chemical alterations, mechanical recycling is one of the most widely implemented plastic recycling technologies globally. Current research efforts are primarily directed toward two key areas: advancing the processing of multi-component waste streams and elucidating the structure–property relationships of the resulting recycled PA.

A breakthrough in recycling multi-component PA waste was achieved by David et al. [18] in 1994. They directly melt-blended post-consumer carpet waste—containing PA6, PA66, polyolefins, and styrene–butadiene rubber (SBR) adhesive—via twin-screw extrusion, eliminating the need for prior component separation. The resulting thermoplastic blend exhibited tensile strength and flexural modulus comparable to those of virgin material, without requiring additional compatibilizers. Similarly, Mondragon et al. [19] processed discarded PA6 fishing nets via direct twin-screw melt extrusion, the degradation in key mechanical properties after recycling was less than 5%. This minimal loss allowed the recycled material to be directly reused in applications such as textiles or injection molding, without the need for chemical depolymerization or additives. Table 1 provides an overview of early mechanical recycling.

Table 1. Early PA Mechanical Recycling Processes.

Raw Material Type	Temperature (°C)	Changes in Product Performance	Cyclic Performance	Reference
Carpet	250–260	Tensile strength 30.7 MPa		[18]
Fishing nets	250–265	Tensile modulus 1.1 GPa	One complete cycle can continue cycling	[19]
Carpet	230	Bending strength 31.7 MPa		[20]
PA6	210–235	Tensile strength increased by 11%	Performance declines after 8 cycles	[21]
PA66/glass fiber (GF) 35	280	Tensile strength 167 MPa	Performance declines over 5 cycles	[22]
PA66/carbon fiber (CF)30	280	Tensile strength 188 MPa	One complete recycling cycle	[23]
PA66/GF35	285	Tensile stress decreased by 16%	Performance slightly degraded after 3 cycles	[24]
PA66/CF30	260–280	Tensile stress decreased by 24.5%	Maintains practical performance after 5 cycles	[25]

Systematic studies have identified three fundamental challenges in the mechanical recycling of PA: (1) changes in molecular weight during reprocessing; (2) incompatibility among constituent materials; (3) degradation of key properties over successive recycling

cycles. To address these challenges, research has focused on two primary strategies: the incorporation of functional additives and the optimization of processing parameters. These key approaches are summarized and compared in Table 2.

Investigating molecular weight changes during mechanical recycling, La Mantia et al. [26] added 500 ppm of the antioxidant P-EPQ during reprocessing, this reaction consumes water, mitigating the water-induced molecular weight decay and consequently slowing the decline in both tensile strength and elongation at break. To enhance the thermal stability of recycled PA6, Dujmić et al. [27] introduced 0.1–2.0 wt% zinc oxide (ZnO) nanoparticles during melt spinning. The ZnO nanoparticles acted as heterogeneous nucleating agents, raising the crystallization temperature from 148 °C to 178 °C. This enhancement in thermal stability was accompanied by the acquisition of antibacterial and UV-resistant properties. This effectively suppresses gelation, which is typically induced by thermal-oxidative crosslinking. Compatibility issues pose a significant challenge in the mechanical recycling of multi-component products. Romeiro et al. [28] demonstrated that commercially available polyisobutylene-grafted maleic anhydride (PI-g-MA) acts as an effective compatibilizer for polyethylene/polyamide (PE/PA) multilayer films. By improving the interfacial adhesion between PE and PA, this approach facilitates the mechanical recycling of such mixed plastic waste. Furthermore, Haddar et al. [29] employed a statistical mixture design (SCMD) approach to optimize the formulation for reprocessing recycled PA6 reinforced with 30 wt% glass fiber (PA6/GF30). This formulation achieved the maximum possible reduction in virgin material input while retaining the required mechanical performance.

Table 2. Overview of Mechanical Recycling Additives.

Raw Material Types	Additives	Temperature (°C)	Performance Changes (After Addition)	Cyclic Performance	Reference
Wet PA6	P-EPQ	240	Tensile stress remains essentially stable	5 times	[26]
Recycled PA6	ZnO nanoparticles	233	Glass transition temperature/Crystallization temperature increased		[27]
PE/PA	PI-g-MA	200	Tensile strength/Elongation at break increased	Secondary performance stability	[28]
PA6	Bruggolen M1251	240–250	Molar mass is essentially stable	No molar mass decrease after 5 recycling cycles	[30]
Recycled PA6/PP	30 wt%GF	225–280	Tensile strength increased		[31]
PA6	Chain Extender DiCE	230–250	Tensile yield strength/Elastic modulus increased		[32]
PA6/thermoplastic elastomer (TPE)	TriEpPOSS MultEpPOSS	230	Izod impact strength/Tensile strength/Young's modulus increased	Can be recycled four times	[33]

During the mechanical recycling of PA, non-polymeric impurities such as dyes, flame retardants and stabilizers impair material performance. To solve this problem, several countermeasures have been developed. Gorreta et al. [34] reviewed dye removal methods, including back stripping, dissolution–precipitation and depolymerization. Green solvents such as 1,4-butanediol can achieve complete decolorization without damaging the polymer backbone. Kovács and Toldy et al. [35] applied flame-retardant coatings based on

hexaphenoxycyclotriphosphazene (HPCTP)/expandable graphite (EG) or red phosphorus (RP) onto all-PA composites. After recycling, the HPCTP/EG coating reduced the peak heat release rate by 35.5% compared to virgin PA, while the RP/EG coating maintained a V-2 rating, demonstrating the durability of the coating approach. Drohsler et al. [36] incorporated the chain extender Joncryl and the antioxidant Irganox during PA66 recycling, which increased the viscosity/average molecular weight by 52% and the oxidation onset temperature by 9 °C. In summary, strategies for managing non-polymeric impurities have shifted from simple removal toward synergistic approaches, advancing the mechanical recycling of PA toward high-value, closed-loop systems.

While additives and process optimization have significantly improved the economic and technical feasibility of mechanical recycling, its long-term application remains challenged by inevitable performance degradation. Su et al. [37] investigated the effects of up to 16 repeated injection molding cycles on the mechanical properties and structure of PA6. Although the chemical structure of PA6 remained unchanged, chain scission, primarily driven by thermal, oxidative, and mechanical stress, resulted in a reduction in molecular weight, a broadening of the molecular weight distribution, and a decrease in melt viscosity. Consequently, the material transitioned gradually from tough and ductile to hard and brittle. In summary, while mechanical recycling demonstrates good feasibility and cost-effectiveness for short- to medium-term cycles, its long-term mechanical reliability requires continuous evaluation and enhancement through advanced material design, fundamental research into aging mechanisms, and the development of process-coupled simulation models.

3. Chemical Recycling

PA possesses remarkable chemical stability, primarily attributed to the resonance within its amide bonds (with a resonance energy of 15–20 kcal mol^{−1}) and the strong hydrogen bonding between amide groups (having a dissociation enthalpy, ΔH_{diss} , of 8–12 kcal mol^{−1}) [38,39]. This inherent stability makes the chemical depolymerization of PA under mild conditions particularly challenging. Common chemical recycling methods for PA include hydrolysis [40–48], solvent-free depolymerization [49–52], hydrogenolysis [53–55] ammonolysis [56–59] and alcoholysis [60–66].

3.1. Hydrolysis

PA hydrolysis is a chemical process in which water molecules cleave the amide bonds along the polymer backbone, yielding carboxyl and amine terminal groups. This chain scission results in shorter polymer chains and a reduction in molecular weight. The hydrolysis rate increases significantly under elevated temperatures (thermal or critical hydrolysis) or in the presence of acid catalysts. Representative reaction equations are illustrated in Figure 3.

Hydrolysis offers a dual advantage for recycling monomer-derived nylon waste: it is an environmentally benign route and a viable method for recovering high-purity monomers [44]. However, conventional neutral hydrolysis necessitates specialized alloy reactors operating at high temperatures and pressures [45,67], entailing high capital investment and ongoing maintenance costs. Meng et al. [68] investigated the macroscopic phase transitions and microscopic hydrolysis mechanisms of PA6 within the temperature range of 240–280 °C. Using in situ monitoring, they delineated the hydrolysis process into four distinct stages: annealing, intermediate formation, transition, and monomerization. Based on these mechanistic insights, a novel cyclic recycling scheme was proposed: PA6 → Low-Molecular-Weight PA6 → Regenerated PA6. The resulting RPA6 exhibited thermal and mechanical properties comparable to those of virgin PA6, while the overall process achieved an 89.9% reduction in energy consumption compared to conventional

hydrolysis, providing a low-energy, high-performance pathway for the sustainable lifecycle management of PA6.

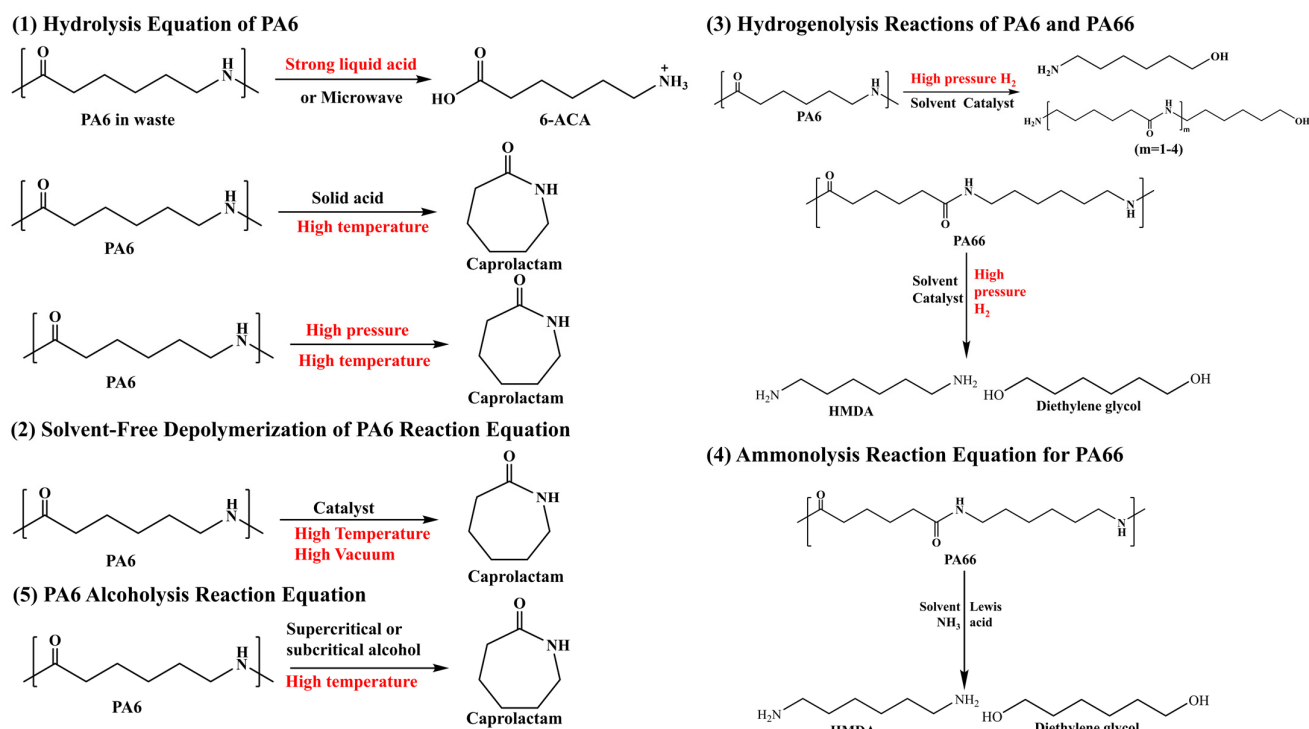


Figure 3. Chemical reaction equations of PA depolymerization.

Acid-catalyzed hydrolysis enhances PA depolymerization by introducing an acid catalyst, which significantly lowers the required reaction severity compared to uncatalyzed or critical hydrolysis. Current implementations of acid-catalyzed hydrolysis for PA are primarily based on two catalyst types: liquid acids and solid acids. Among liquid acid catalysts, hydrochloric acid is widely used, while sulfuric acid and formic acid have also been studied. For instance, Shukla et al. [69] conducted a study on the acid-catalyzed depolymerization of waste nylon 6 fibers, achieving decomposition by refluxing in 90% formic acid, 30–60% hydrochloric acid or 15% sulfuric acid at their respective boiling points for varying durations. To mitigate equipment corrosion from strong mineral acids, Khuntia et al. [70] investigated less corrosive organic acids, including methanesulfonic acid (MSA), benzenesulfonic acid (BSA), and p-toluenesulfonic acid (p-TSA). These acids achieved oligomer recovery yields ranging from 81.09% to 96.15%. To improve the efficiency and incomplete degradation of liquid-acid depolymerization, Bäckström et al. [71] developed a microwave-assisted, HCl-catalyzed hydrothermal process. Treatment of 0.5 g of pure PA6 or PA66 pellets with HCl (0.1 g/mL) at 200 °C for 30 min rapidly yielded the corresponding monomers. Solid acid catalysts offer key advantages including low corrosivity, high recyclability and tunable selectivity. Yi et al. [72] developed a recyclable solid phosphoric acid catalyst for PA6 depolymerization. Compared to homogeneous liquid acids, this catalyst enhanced target monomer recovery while eliminating equipment corrosion concerns and maintained a monomer yield of approximately 65% over multiple recycling cycles. Jiang et al. [73] employed a solid Lewis acid catalyst L-Nb₂O₅ to address the challenges of low amide bond reactivity and catalyst recovery under mild conditions for PA6 depolymerization. This catalyst achieved a caprolactam (CPL) yield of 82.2%, with minimal activity loss over five consecutive cycles. The acid catalyzed hydrolysis technology of PA has made significant progress, but both liquid and solid acid catalytic systems still face some technical

and economic challenges. Mitigating equipment corrosion, reducing energy consumption, and solving wastewater issues remain the focus of further research.

3.2. Solvent-Free Depolymerization

The alkaline depolymerization of PA6 is typically conducted under solvent-free conditions. The process operates under vacuum, enabling the direct distillation and recovery of caprolactam without the need for complex downstream purification units. Furthermore, the solvent-free nature of the process eliminates the energy-intensive steps of heating and recovering large volumes of solvent [74]. A key challenge of solvent-free PA6 depolymerization, however, is the typically high catalyst loading required to drive the reaction effectively. Moreover, these systems often require elevated temperatures and very low pressures to achieve efficient chain cleavage and monomer formation. Consequently, recent research has focused on strategies to lower the required catalyst loading and to achieve efficient depolymerization at reduced temperatures. Representative reaction equation is illustrated in Figure 3.

Wursthorn et al. [49] reported a system where lanthanide metal complexes $\text{Ln}(\text{N}(\text{TMS})_2)_3$ catalyze the depolymerization of PA6. Using a solvent-free process under static vacuum at 240 °C, efficient conversion of PA6 to CPL was achieved within 4 h with a catalyst loading of 5 mol%. Building on this foundation, Ye et al. [52] developed two highly efficient catalytic systems through precise engineering of the lanthanide ligand structures. $\text{Cp}^*_2\text{LaCH}(\text{TMS})_2$ ($\text{Cp}^* = \eta^5\text{-C}_5\text{Me}_5$, $\text{TMS} = \text{SiMe}_3$) utilizes its exceptional electron-donating ability to rapidly initiate amide bond cleavage through protonation of the La–C bond, thereby significantly lowering the reaction energy barrier. Under static vacuum at 240 °C, a CPL yield of 99% was achieved with only 0.2 mol% catalyst after just 1 h. $\text{Me}_2\text{SiCp}''_2\text{YCH}(\text{TMS})_2$, ($\text{Cp}'' = \eta^5\text{-C}_5\text{Me}_4$) operates via a different mechanism. The chelating effect rigidifies the ligand spatial configuration and increases the “grip angle”. This design resolves transition-state crowding induced by the small ionic radius of Y^{3+} and concurrently enhances the thermal stability of the catalyst.

While lanthanide-based catalysts pioneered the efficient activation of amide bonds under solvent-free conditions, their practical application is limited by high cost, catalyst loadings and constrained applicability. In contrast, alkali catalysts offer distinct advantages of low cost and easy availability. Chen et al. [50] employed a low-cost, commercially available mixed alkali catalyst (NaOH/KOH) to achieve the thermal depolymerization of both virgin and post-consumer PA6 under solvent-free conditions. Notably, the recovered ϵ -CPL was successfully repolymerized into regenerated PA6, whose chemical structure, thermal properties, and mechanical performance were nearly identical to those of virgin PA6. In a separate study, Chen et al. [51] utilized the phosphorus–nitrogen superbase $t\text{-BuP}_4$ as a green, metal-free catalyst for PA6 depolymerization. For PA6 pretreated with KOH to neutralize carboxyl end groups, a catalyst loading of only 0.2 mol% was sufficient. Reactions were conducted in a solvent-free melt under vacuum (0.1 mbar) at 250 °C, PA6 was quantitatively depolymerized to CPL yielding 92–99%.

Despite its economic benefits from eliminating solvent use and achieving high CPL yields, PA6 solvent-free recycling technology presents several limitations. From a process standpoint, the technology requires maintaining high vacuum and elevated temperature conditions to facilitate CPL separation. The inorganic bases used can corrode standard industrial equipment, most current research on solvent-free catalysts for PA6 recycling is still at the pilot-scale stage.

3.3. Hydrogenolysis

Catalytic hydrogenation is an atom-efficient, green, and sustainable organic transformation. It avoids the stoichiometric waste associated with traditional reducing agents, and the required hydrogen source can potentially be derived from renewable resources [75]. However, the solvent resistance and high rigidity of PA have hindered significant progress in the catalytic hydrogenation of conventional nylons in recent years. The corresponding hydrogenolysis reactions for PA6 and PA66 are illustrated in Figure 3. A breakthrough was reported by the team of Amit Kumar [53], who demonstrated the catalytic hydrolytic depolymerization of durable nylons and polyurethanes using a ruthenium pincer catalyst in DMSO. This work addressed a prior gap in conventional nylon recycling that did not utilize hydrogenation. Subsequently, Wei Zhou's team [76] advanced the methodology by employing THF as the solvent, achieving both an improved monomer yield and the first successful application of this technology to industrial-grade materials. They also identified that carboxylic acid end groups in PA66 inhibit catalyst activity. This insight informs necessary pretreatment steps for industrial-grade nylon, thereby advancing the technology toward practical application.

3.4. Ammonolysis

Among chemical recycling methods for PA, ammonolysis is of research interest due to its distinctive reaction pathway. This process cleaves the polymer chains yield valuable nitrogen-containing building blocks while concurrently generating nitrogen-functionalized derivatives. Early and representative work in this area is documented in two DuPont patents [59,77]. These patents demonstrate the effective depolymerization of PA6/PA66 mixtures via amination, reporting monomer yields of 88% and 61%, respectively. From a thermodynamic perspective, the hydrolysis of secondary amide bonds is a reversible equilibrium reaction. The elevated temperatures used in these patents favor the product side by providing the requisite endothermic driving force, enabling high reaction efficiency. Robin Coeck [57] developed an improved amoxidation process. This method employs a combined amination-hydrogenation catalysis to drive the reaction to completion. The primary amide generated in situ is continuously hydrogenated to the corresponding amine, thereby rendering the overall process irreversible. This approach enhances energy efficiency and enables the concerted valorization of PA waste. In a complementary approach, Stuyck et al. [58] focused on optimizing the amination conditions. They achieved PA66 depolymerization under mild conditions using ammonia as the amination reagent and waste glycerol (a biorefinery by-product) as the solvent (Figure 3). This approach circumvents the high-temperature and high-pressure requirements of conventional amination processes, thereby combining environmental sustainability with economic viability.

3.5. Alcoholysis

For nylon depolymerization and recycling, alcoholysis emerges as a pivotal technology that addresses the limitations of traditional methods while aligning with the goals of a polymer circular economy. Compared to conventional methods, the core advantage of alcoholysis lies in its flexible and precise product control. Through the rational selection and tailoring of the alcohol medium, alcoholysis can achieve targeted monomer recovery and simultaneously convert nylon into value-added chemical intermediates. Kamimura et al. demonstrated that supercritical secondary and tertiary alcohols are highly effective for depolymerizing PA6 into CPL [62]. Under optimized conditions (370 °C, 1.5 h), PA6 was converted to ϵ -caprolactam in near-quantitative yields of 93–97% with high purity (Figure 3). Subsequently, Kaweetirawatt et al. [64] investigated the underlying mechanism using combined quantum mechanical/molecular mechanical free energy perturbation

calculations. Their calculations revealed that during PA6 depolymerization in supercritical alcohols (e.g., methanol, isopropanol), the reaction preferentially follows an intermolecular pathway. This involves initial alcoholysis to form an aminohexanoate intermediate, followed by its cyclization to ϵ -caprolactam. Experimentally, supercritical isopropanol effectively suppressed N-alkylation side reactions, yielding 91% ϵ -caprolactam. In contrast, supercritical methanol promoted side reactions, resulting in a much lower yield of only 14%. This work further validates the superior efficacy of supercritical secondary alcohols for the selective production of CPL. Alcoholysis of PA has emerged as an efficient chemical recycling pathway for the valorization of waste nylon into high-value chemicals. Using solvents like supercritical methanol or glycols, PA undergo controlled cleavage at moderate temperatures to yield valuable products such as ω -hydroxyalkanoates. These products command a significantly higher market value than conventional monomers like caprolactam, enabling the economic upcycling of plastic waste [60,61,63–66].

4. New Paradigms in the Circular Economy

As one of the most widely produced and versatile engineering plastics, PA has made its recycling a topic of significant global interest. To improve the economic viability of PA recycling and overcome the limitations of conventional methods, developing more efficient and innovative recovery technologies is crucial. Such advancements are essential for advancing the circular economy and meeting the growing demand for sustainable PA. Accordingly, this chapter explores innovative domains in PA recycling, highlighting emerging directions for a PA circular economy through upcycling, molecular design, biochemical processes, and solvent recovery.

4.1. Upcycling: From Low-Value Waste to High-Value Products

Enhancing the economic viability of PA recycling requires integrating depolymerization with the downstream conversion of degradation products into high-value compounds. This integrated approach enables the valorization of low-value waste into high-value products, representing a transformative advance in recycling [78].

Tertiary amines are high-value chemicals used as softeners, dye synthesis intermediates and pharmaceutical precursors. Their economic value substantially exceeds that of base monomers or recycled plastics obtained from conventional PA recovery [79–82]. Tang et al. [83] demonstrated the efficient conversion of PA waste under mild conditions (180 °C, 5 MPa H₂) using acetic acid as a solvent. Acetic acid serves a triple role: it disrupts the crystalline structure of nylon, catalyzes acid hydrolysis, and acts as an alkylating agent. This process achieves 100% selectivity for tertiary amines alongside high yields of carboxylic acid monomers, exemplifying an efficient upcycling pathway.

Alcohols are pivotal reagents for the high-value depolymerization of PA, offering key advantages: excellent solvent compatibility, tunable reactivity, direct access to value-added products, and mild reaction conditions. In a related approach, methyl toluenesulfonate (TsOMe) serves as an in situ precursor to generate p-toluenesulfonic acid (TsOH) in alcoholic solvents. Yang et al. [84] employed this TsOMe/TsOH system to efficiently depolymerize a wide range of PA via alcoholysis under mild conditions (140 °C), successfully converting PA6, PA66, PA11, and PA12 into high-value monomer precursors. For instance, PA6 is transformed into methyl 6-aminohexanoate, which can be subsequently cyclized to ϵ -CPL, while PA66 yields the readily separable diamine tosylate salt and corresponding diesters. Liu et al. [85] developed a versatile and metal-free method for direct amide alcoholysis, mediated by the Lewis acid HBF₄ under mild conditions. This method features an exceptionally broad substrate scope, efficiently converting not only aromatic and aliphatic primary amides but also challenging secondary and tertiary amides, as well as thioamides,

into the corresponding esters in high yields. The practicality of this approach was confirmed through gram-scale experiments and its application in the efficient one-step synthesis of pharmaceutical intermediates, such as the local anesthetic benzocaine and the anticancer agent zinostatin (Table 3 summarizes the scaled-up process).

Research into the biotechnological upcycling of PA has demonstrated a promising synergistic approach. The process begins with the acid hydrolysis of PA into a mixture of monomers and linear/cyclic oligomers. Subsequently, the bacterium *Pseudomonas putida* KT2440 was adapted to assimilate the monomeric hydrolysis products. The substrate range of the engineered strain was then expanded to include linear and cyclic oligomers through the heterologous expression of nylon oligomer hydrolase genes (NylA/B/C) from *Bacillus* sp. Finally, by introducing the phaCAB operon from *Pseudomonas aeruginosa*, the engineered strain was enabled to efficiently convert the PA6 hydrolysate into polyhydroxyalkanoates (PHAs), such as polyhydroxybutyrate, alongside other valuable biochemicals [86,87]. This integrated strategy circumvents the high-energy consumption purification process and overcomes the limitations of traditional recycling technologies, establishing an innovative chemical biology platform for the sustainable upgrading and recycling of PA waste [88].

Table 3. Overview of PA Value Recovery.

Substrate	Product	Medium	Catalyst	Yield	Reference
Various PA	Secondary amine Carboxylic acid	Acetic acid	Mo ₁ Rh _{1,N} /TiO ₂	90%	[83]
PA6/PA66/PA11/PA12	6-Methoxy-6-oxohexan-1-aminium tosylate	methanol	TsOMe	CPL96%	[84]
Various amides	Corresponding ester	alcohol	48 wt% HBF ₄	Glass fiber 96%	[85]
PA6	Polyhydroxybutyrate (PHB)	H ₂ SO ₄		85–99%	[88]
PA6	Thermoplastic polyamide elastomer (TPAE)	ethylene glycol (EG)	Phosphoric acid		[89]
Poly(p-phenylene terephthamide) (PPTA)	Terephthalic acid (TPA)/p-Phenylenediamine (PPD)	n-butanol	NaOH	TPA 92.0% PPD 91.5%	[90]

4.2. Molecular Design: Innovation in Function and Recyclability of Novel PA

Traditional PA materials face multiple challenges to sustainable development. Building upon research in mechanical and chemical recycling, a lot of the novel PA materials have been developed through strategies such as process innovation, molecular design, and the introduction of dynamic bonds (Figure 4, Table 4). These materials achieve enhanced performance alongside efficient recyclability, providing an innovative pathway for closed-loop recycling of PA. These novel PA combine engineering-grade properties with efficient chemical or physical recyclability, addressing the classic trade-off between performance and recyclability.

The molecular design of novel PA begins with the custom synthesis of lactam monomers featuring specific functional structures. These monomers are then polymerized into materials using controlled methods. This innovative monomer design serves two core functions: (1) ring structure modification and precise introduction of functional groups endowing the resulting PA with superior intrinsic mechanical properties; (2) regulation of the monomer's ring strain, electronic effects, and steric hindrance optimizes the thermodynamics and kinetics of both polymerization and depolymerization. Consequently, the PA materials can undergo efficient and selective depolymerization under mild catalytic conditions, enabling the targeted recovery of high-purity monomers.

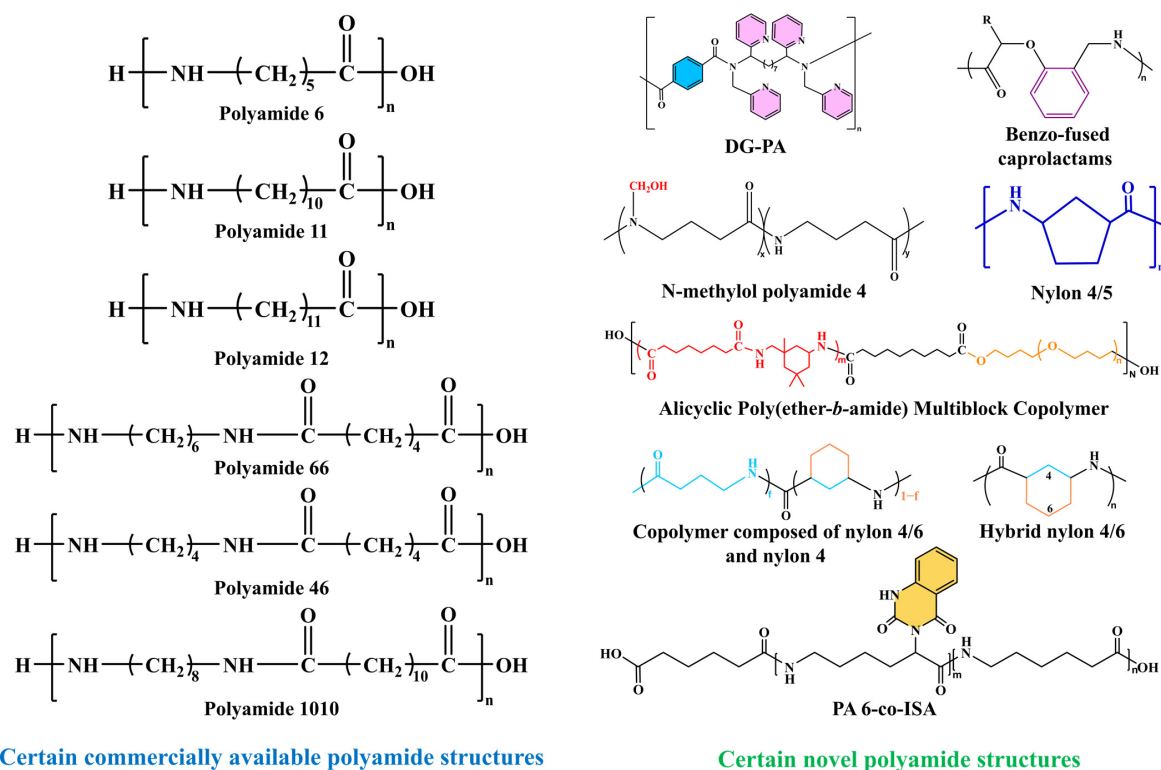


Figure 4. Certain commercially available and novel PA structure.

Table 4. Overview of Parameters for New PA (aromatic polyamide with pendent furan groups (fPA), α -dimethyl substituted caprolactam (α -DMCL), γ -dimethyl substituted caprolactam (γ -DMCL), poly(ether-*b*-amide) multiblock copolymers (PEBAs), 5-azabicyclo[2.2.1]octan-6-one (5/6-LM), benzo-fused lactams (BLM)).

Material Type	Advantages (Compared to Traditional PA)	Recycling Conditions	Reference
Nylon 4/6	Optically transparent, high thermal stability, melt-processable and recyclable	ZnCl ₂ -290 °C	[91]
DG-PA	Recyclability significantly improved	In (OTf) ₃ -160 °C	[92]
PA 6-co-ISA	Enhanced recyclability and flame retardancy	NaOH/KOH-260–300 °C	[93]
P(α -DMCL)	Reduction in depolymerization temperature, transparent, high-toughness properties	CL-K 5 mol%	[94]
P(γ -DMCL)	Enhanced performance, durability and recyclability	200 °C 4 h	[95]
C ₆₀ /fPA composites	Cyclic enhancement	DMF-120 °C Reshapes	[96]
Cross-linked PA networks	High mechanical toughness, efficient self-healing capability, optical transparency, soluble recyclability	Decomposes above 140 °C	[97]
PEBAs	High mechanical strength, exceptional heat resistance, highly recyclable	DMAc/HCl-room temperature	[98]
PA-B ₃ O ₃	Simple synthesis, superior chemical recyclability	ZnCl ₂ -60 °C	[99]
5/6-LM	Thermal properties, mechanical properties, and biodegradability can be regulated through composition control	Low vacuum for 16 h	[100]
Star-shaped PA 4/6	Methylation effectively regulates the crystallinity, thermal properties, mechanical properties, and biodegradability of PA4	Standard activated sludge system: 27 °C, 29 days	[101]
N-methylol PA 4	Superior water resistance, high transparency, adjustable mechanical properties, mild chemical recycling ability	Standard activated sludge system: 27 °C, 35 days	[102]
P(BLM)		Dilute DMF solution 100–150 °C, 24 h	[102]

Cywar et al. [91] designed a novel hybrid bridged bicyclic lactam, 5/7-LM. Polymerization via anionic ring-opening polymerization (AROP) yielded the corresponding PA, nylon 4/6. The bicyclic structure endowed the resulting nylon 4/6 with a nanocrystalline morphology, high thermal stability, and optical clarity. Copolymerizing 5/7-LM with 2-pyrrolidone (5-LM) enabled the spatial steric hindrance of the bridged bicyclic unit to regulate the polymerization equilibrium, yielding an amorphous copolymer. The resulting copolymer underwent depolymerization using ZnCl_2 as a catalyst, enabling the recovery of the constituent monomer mixture. Shiraki et al. [92] designed a novel diamine monomer featuring pyridine-based directing groups. Its polycondensation with terephthaloyl chloride afforded the target polyamide DG-PA. These pyridine-based directing groups served a dual function: modulating the material's properties and providing specific active sites for catalytic depolymerization. An In(III) catalyst selectively cleaved the adjacent amide bonds via coordination to these pyridine groups. This catalytic cleavage enabled the efficient depolymerization of DG-PA into the original diester and diamine monomers. The resulting diester was then hydrolyzed and chlorinated to quantitatively regenerate terephthaloyl chloride, finalizing the closed-loop chemical recycling process.

In addition, researchers employ commercial PA or conventional lactam monomers as the primary material platform. Without modifying the essential backbone architecture or the amide linkage configuration, strategies such as substituent introduction, functional-group grafting, and copolymerization are employed to fine-tune the polymer structure. He et al. [93] employed conventional ϵ -caprolactam as a precursor for functionalization. Through ring-opening grafting of caprolactam or the incorporation of its flame-retardant derivatives, they imparted UL94 V-0 grade flame retardancy alongside excellent mechanical stability to the PA. Under mild conditions, the modified PA could be depolymerized to recover both ϵ -CPL and the flame-retardant monomers. Chen et al. [94] modified a commercial PA by introducing dimethyl substituents. The steric hindrance of these substituents reduced the resonance stability of the amide bonds and weakened hydrogen bonding interactions. This enabled hydrolytic degradation of the PA under mild conditions, achieving over 90% monomer recovery. Concurrently, the material maintained a thermal decomposition temperature above 320 °C and a tensile strength exceeding 40 MPa. This successfully achieved the modification goal of enhancing recyclability without compromising key material properties.

Furthermore, the incorporation of dynamic covalent or non-covalent bonds as key cross-linking and functional units enables the synergistic optimization of crucial application properties, such as mechanical strength, thermal stability and recycling efficiency. This is achieved through the dynamic and reversible processes of bond formation, cleavage, and reorganization. The reversible nature of these dynamic bonds constitutes the core design logic for this class of PA. On one hand, cross-linking via dynamic bonds constructs stable three-dimensional networks, which significantly enhance structural integrity and service performance. On the other hand, these bonds can undergo selective cleavage under mild external stimuli, thereby providing low-energy, highly selective pathways for depolymerization and material recycling. For instance, Chen et al. [95] designed and synthesized an aromatic PA bearing pendent furan groups (fPA), utilizing Diels-Alder (D-A) bonds as the core dynamic cross-linking units. A crosslinked network was constructed through the thermoreversible D-A reaction between the furan groups and fullerene (C_{60}), significantly enhancing the tensile strength and thermal stability of the fPA matrix. At 140 °C, the retro-D-A reaction occurs, leading to the dissociation of crosslinks and enabling the complete dissolution of the composite for recycling. Furthermore, the material exhibited excellent high-temperature shape memory performance, perfectly embodying the “crosslinking for reinforcement—dissociation for recycling” dynamic design concept.

4.3. Chemical-Biological Coupling: Synergy of Pretreatment and Biotransformation

PA materials exhibit exceptional chemical stability, primarily due to the resonance stabilization of their amide bonds and strong inter-chain hydrogen bonding. These inherent structural features render chemical depolymerization under mild conditions particularly challenging. Biological recycling methods offer distinct advantages, including environmental benignity, low energy consumption, and the generation of non-toxic byproducts. Extensive research on the bioenzymatic degradation of Polyethylene terephthalate (PET) has spurred significant attention and led to technological breakthroughs in the broader field of enzymatic plastic recycling. However, achieving the complete depolymerization of PA solely via enzymatic methods currently faces significant limitations. For instance, screening work by Bell et al. identified a thermostabilized N-terminal nucleophilic hydrolase (NylC_k-TS, $T_m = 87.4$ °C) as the most efficient among 40 candidates. Yet, when applied to PA6 film, it achieved a maximum degradation rate of only 0.67 wt%, and the reaction plateaued after 10 days. Supplementing with fresh enzyme did not restore degradation activity, indicating that limited substrate accessibility is the core constraint. This limitation arises from the dense hydrogen-bonding network and high crystallinity of PA6, which prevent enzyme penetration into the polymer bulk, thereby restricting catalysis to a limited number of accessible surface sites [103]. Consequently, a single-step enzymatic hydrolysis process is insufficient to meet industrial recycling requirements. A breakthrough in efficiency likely requires an integrated strategy that couples chemical pretreatment with subsequent enzymatic hydrolysis.

To address this challenge, Shiraishi et al. [104] pioneered an integrated recovery strategy combining chemical pretreatment with enzymatic hydrolysis. The chemical pretreatment, involving homogeneous dispersion in a solvent, disrupted the PA's hydrogen-bonding network and reduced its crystallinity. This markedly increases the substrate's specific surface area and boosts the yield of soluble oligomers by 8.7-fold. Subsequent acid-induced oligomerization further enhanced the water solubility and enzymatic susceptibility of the nylon-derived fragments. The subsequent synergistic hydrolysis by NylC and NylB amidases ultimately achieved monomer yields exceeding 95% for both PA6 and PA66. This addresses the key drawbacks of the individual methods: residual oligomers from chemical depolymerization and the low efficiency of stand-alone enzymatic hydrolysis. However, the high water solubility of the recovered monomer, aminocaproic acid [105], necessitates further downstream processing for its separation and purification [104]. In addition, Witt et al. demonstrated that an integrated chemical–biological strategy—combining chemical hydrolysis with engineered microbial conversion—effectively addresses the challenge of PA monomer recovery while enabling the high-value conversion of hydrolysis products into valuable biochemicals [88]. The specific process is outlined in Figure 5.

4.4. Solvent Recovery: Achieving Mild and Efficient PA Separation

Solvent recovery technology utilizes a highly selective solvent system to achieve precise separation of PA from mixed wastes. This is accomplished via a reversible dissolution-precipitation mechanism under mild conditions [106]. This approach not only recovers high-purity PA with chemical structures and mechanical properties akin to the virgin material but also facilitates the concurrent recovery of other valuable components from the mixture. Consequently, this method substantially reduces energy consumption and the associated carbon footprint. It thus presents a promising innovative pathway for addressing the recycling of mixed PA waste and advancing a circular economy. Detailed process parameters are summarized in Table 5.

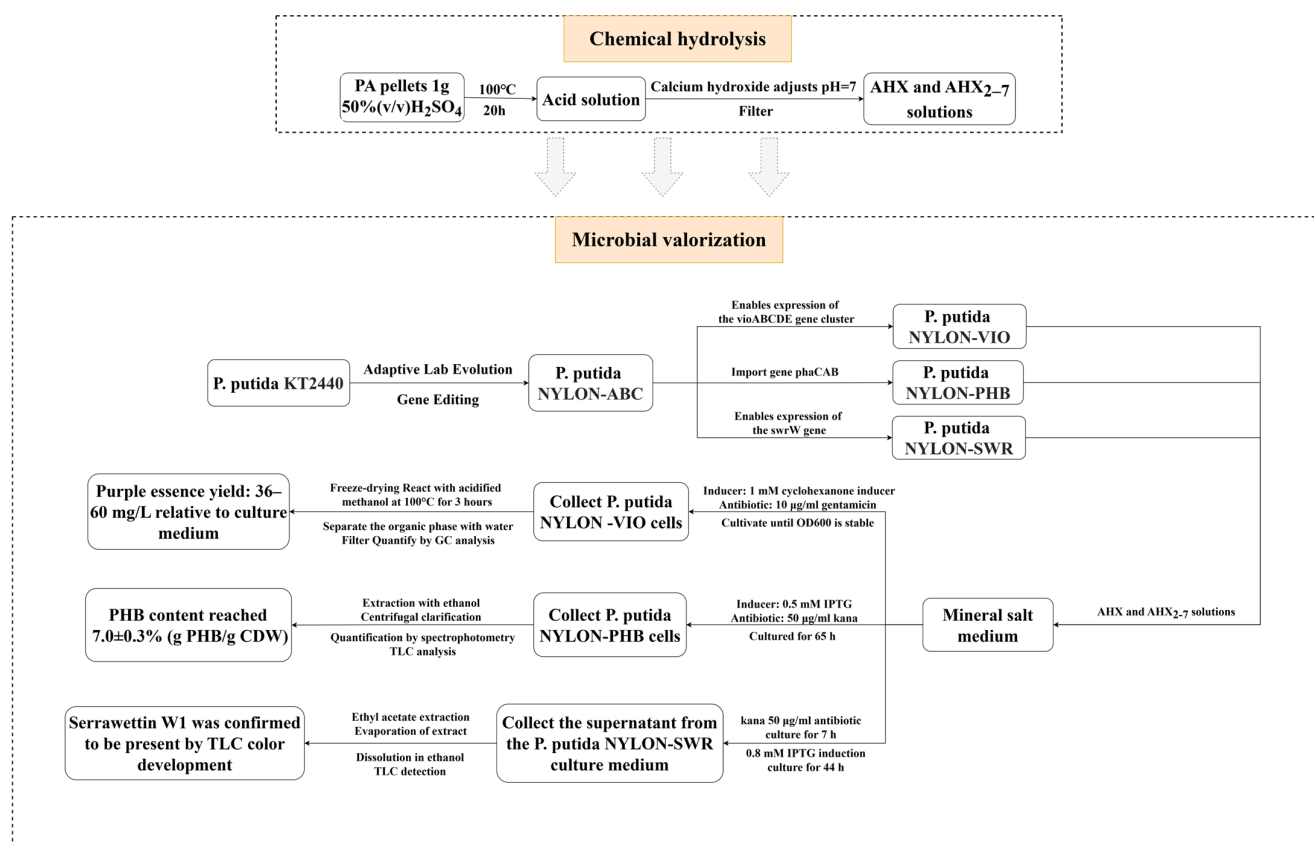


Figure 5. Specific steps for achieving upgraded recycling through biochemical coupling.

Table 5. Overview of Solvent Recovery for Polyamide.

Solvent System	Dissolution Conditions	Resettling Method	Material Composition	Yield	References
85% Formic Acid	50 °C	Solvent evaporation	PA6/polyurethane (PU)/PET/Cotton/GF	95%	[107]
85% Formic Acid	50 °C	Antisolvent H ₂ O	PA6/PU/PET/Cotton	93%	[107]
Formic Acid/Weak Hydrogen-Bond-Donor Co-solvent System	25–30 °C 0.1–1 h	Antisolvent Acetone/H ₂ O	PA6/PE/polyimide (PI)/GF/CF/Cu	99.2%	[108]
CEW	Shake at room temperature for 1 h	Antisolvent H ₂ O	PA66/Wool	93.20%	[109]
CEW	Shake at room temperature for 60 h	Antisolvent H ₂ O	PA66/Viscose Cellulose	80–90%	[110]

Formic acid is a common solvent for PA recovery. Tonsi et al. [107] performed a life cycle assessment (LCA) to evaluate PA recovery via selective dissolution in formic acid. The study compared two recovery processes: solvent evaporation precipitation and anti-solvent precipitation, indicating that the solvent evaporation process exhibited the lowest global warming potential (GWP). Additionally, this solvent-based technology can process mixed PA waste streams that are not amenable to mechanical or chemical recycling. Compared to virgin PA6 production, the overall environmental impact was reduced by more than 75%. This confirms the environmental feasibility and advantages of integrating solvent recovery into a PA circular economy. Building on this work, Tanks et al. [108] developed a composite solvent system comprising formic acid and weak hydrogen bond donor co-solvents. This system enables the rapid dissolution of diverse PAs—including short-chain, long-chain,

and semi-aromatic types—at room temperature without chain degradation. Simultaneously, the system enabled the efficient recovery of fillers such as carbon fiber, glass fiber, and metals from composite waste. Further validation via gram-scale experiments and upcycling demonstrated that the recovered PA could be repurposed for synthesizing pharmaceuticals or combined with carbon nanotubes to fabricate high-performance composites, carbon footprint of this process was only 1/5 to 1/8 that of virgin PA production.

Separately, Rietzler et al. [109] investigated a green, non-destructive method for recovering PA from mixed textile waste. They proposed a CaCl_2 /ethanol/water (CEW) solvent system that achieves selective PA dissolution via reversible complexation with Ca^{2+} ions. Experimental verification confirmed that the recovered PA exhibited chemical structures and thermal properties comparable to virgin material, achieving a recovery rate of 93.2%. Building on this concept, Manian et al. [110] employed the CEW solvent system to selectively separate and recover PA66 from blends with cellulose fibers. The study found that cellulose fibers treated with CEW retained their tensile strength without apparent solvent damage. However, some residual PA66 remained on the fiber surfaces, most of which was removable by mechanical carding. PA66 recovery rates reached 80–90%.

5. Conclusions

As one of the five major engineering plastics, PA has a global annual consumption exceeding 8 million tons. The accumulation of PA waste has positioned it as a central challenge in combating plastic pollution. This review systematically synthesizes the research progress in PA recycling over the past five years. By integrating recent technological breakthroughs with persistent industrial challenges, this review concludes with the following perspectives and future directions. Figure 6 shows the evolution of PA recycling technology and the forecasts for future trends.

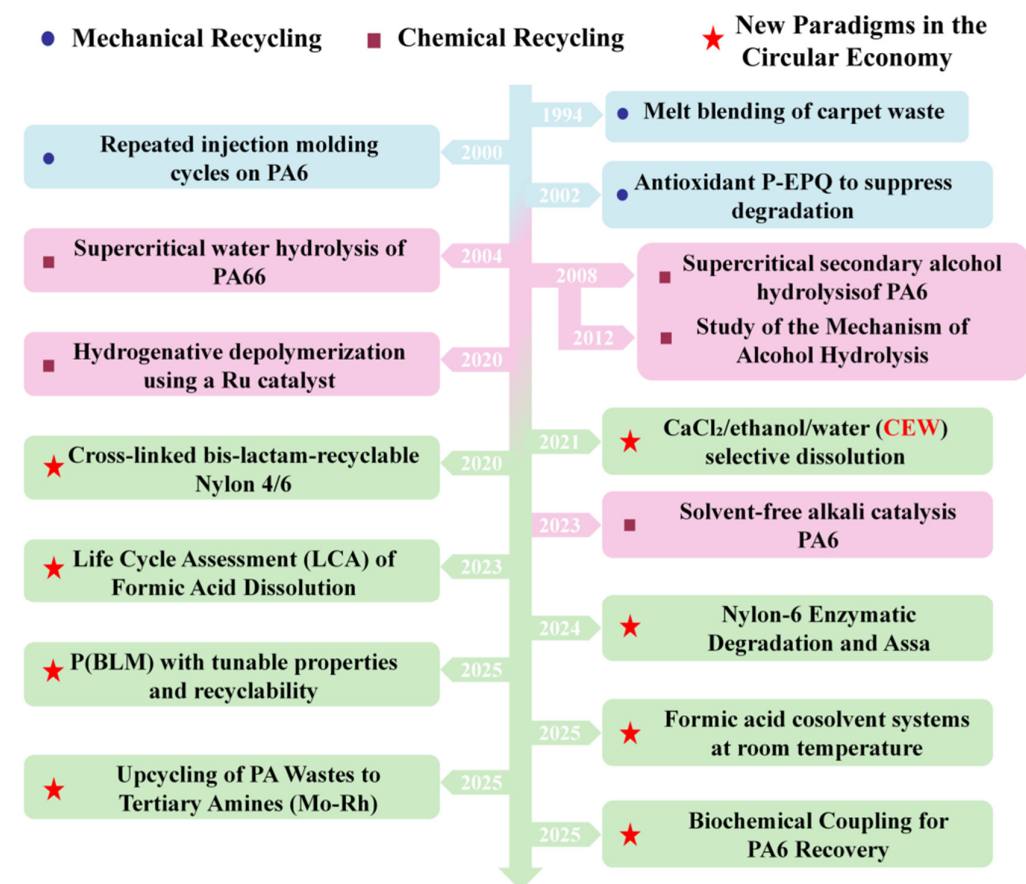


Figure 6. The Evolution of PA Recycling Technology and Forecasts for Future Trends.

Mechanical recycling offers significant economic and environmental advantages for short- to medium-term recycling loops, significant progress has been made in enabling multiple extrusion cycles and the reuse of fiber-reinforced composites. However, key challenges persist for long-term recycling, future efforts should focus on elucidating aging mechanisms and developing reliable lifetime prediction models, which is crucial for enabling the stable and large-scale application of mechanically recycled materials. Chemical recycling addresses the inherent limitations of material downcycling, positioning itself as the core pathway for achieving closed-loop, high-value utilization of PA. Technologies including hydrolysis, alcoholysis, ammoxidation, hydrogenolysis, and catalyst-mediated depolymerization are progressively advancing from fundamental research toward pilot-scale implementation. However, key challenges persist for industrial-scale implementation. These include reducing catalyst costs, improving the corrosion resistance of reaction vessels, optimizing continuous reactor design, and managing heat and mass transfer during process scale-up.

Innovative technology streams—exemplified by upcycling, molecular design, chemo-biological coupling, and solvent recovery—are emerging as pivotal new pathways for advancing PA circularity. Upcycling employs targeted chemical strategies to precisely convert waste PA into products with significantly higher market value. The market value of these upcycled products can be 2 to 5 times higher than that of conventional PA monomers, substantially improving the economic driver for recycling investments. Through molecular design, novel monomers are custom-synthesized. Their precise polymerization, often coupled with the incorporation of dynamic functional units like Diels–Alder adducts or hydrogen bonding networks, has successfully yielded a range of high-performance, chemically recyclable PA. Chemo-biological coupling integrates the efficient depolymerization from chemical pretreatment with the green, high-value conversion potential of biological processes. This hybrid approach provides a promising low-energy route for recycling complex or mixed waste streams. Solvent recovery utilizes tailored systems to achieve high-purity PA recovery from mixed waste under mild conditions via selective dissolution–precipitation. This technology effectively combines environmental benefits with economic feasibility. Table 6 shows the comprehensive comparison of the technical and economic viability of PA recycling, the data is based on the processing of 1 ton of PA waste. Reagent costs are calculated as one-time expenses at industrial-scale prices, while process costs are estimated for industrial-scale operations. Total revenue is determined using market prices of the main products and the yields reported in the literature. Profit is defined as revenue minus the combined reagent and process costs. TRL refers to the Technology Readiness Level. All data in the table are derived from representative literature sources that present the most economically viable technical routes.

In summary, this review has examined recent advances in PA recycling, encompassing mechanical, chemical, and emerging innovative approaches, supported by representative case studies. It has also summarized prospects from the perspectives of economic viability, environmental impact and resource efficiency, offering valuable insights to guide the industrialization and sustainable innovation of PA recycling technologies. Innovative recycling is emerging as pivotal driver for advancing circularity in PA use, these four innovative pathways hold significant potential to become central to the sustainable development of PA, offering promising solutions to meet the growing demands for a circular economy and greener material cycles.

Table 6. Comprehensive Comparison of the Technical and Economic Viability of PA Recycling Technologies.

Recycling Technology	Reagent Costs \$	Processing Costs \$	Total Revenue \$	Profit \$	TRL	References
Mechanical Recycling	-	2130	2800–3200	670–1070	9	[21]
Acidic Hydrolysis (SPA)	3030	930	1350	-	4	[73]
Solvent-free Depolymerization	90	900	1830	840	5	[50]
Hydrogenolysis	>8000	550–600	3800	-	3	[75]
Ammonolysis	2200–3300	130	1400–1700	-	3	[58]
Alcoholysis	1670–3340	250–330	1930	-	3–4	[111]
Upcycling	13,300	240–340	14,500	900–1000	4	[62]
Chemo-biological Coupling	>5500	100	1350	-	4	[104]
Solvent-based Selective Recovery	300	60	2200	1840–2100	3–4	[110]

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References

- Li, Y.; Tao, L.; Wang, Q.; Wang, F.; Li, G.; Song, M. Potential Health Impact of Microplastics: A Review of Environmental Distribution, Human Exposure, and Toxic Effects. *Environ. Health* **2023**, *1*, 249–257. [\[CrossRef\]](#) [\[PubMed\]](#)
- Winiarska, E.; Jutel, M.; Zemelka-Wiacek, M. The potential impact of nano- and microplastics on human health: Understanding human health risks. *Environ. Res.* **2024**, *251*, 118535. [\[CrossRef\]](#) [\[PubMed\]](#)
- Muhammad, P.; Mohammad, F.; Mohammad, J.; Mohini, S. Polyamides: Developments and Applications Towards Next-Generation Engineered Plastics. *Curr. Org. Synth.* **2017**, *14*, 146–155. [\[CrossRef\]](#)
- Passinger, T.; Schmohl, L.; Zarges, J.-C.; Resch, J.; Heim, H.-P.; Bonten, C. Investigation of the UV-aging behavior of bio-based polyamides for automotive interiors. *Polym. Test.* **2025**, *146*, 108796. [\[CrossRef\]](#)
- Holbery, J.; Houston, D. Natural-fiber-reinforced polymer composites in automotive applications. *JOM* **2006**, *58*, 80–86. [\[CrossRef\]](#)
- Hirschberg, V.; Rodrigue, D. Recycling of polyamides: Processes and conditions. *J. Polym. Sci.* **2023**, *61*, 1937–1958. [\[CrossRef\]](#)
- De Falco, F.; Gullo, M.P.; Gentile, G.; Di Pace, E.; Cocca, M.; Gelabert, L.; Brouta-Agnésa, M.; Rovira, A.; Escudero, R.; Villalba, R.; et al. Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. *Environ. Pollut.* **2018**, *236*, 916–925. [\[CrossRef\]](#)
- Thompson, R.C.; Olsen, Y.; Mitchell, R.P.; Davis, A.; Rowland, S.J.; John, A.W.G.; McGonigle, D.; Russell, A.E. Lost at Sea: Where Is All the Plastic? *Science* **2004**, *304*, 838. [\[CrossRef\]](#)
- Deshoules, Q.; Le Gall, M.; Dreanno, C.; Arhant, M.; Priour, D.; Le Gac, P.Y. Modelling pure polyamide 6 hydrolysis: Influence of water content in the amorphous phase. *Polym. Degrad. Stab.* **2021**, *183*, 109435. [\[CrossRef\]](#)
- Geyer, R.; Jambeck, J.R.; Law, K.L. Production, use, and fate of all plastics ever made. *Sci. Adv.* **2017**, *3*, e1700782. [\[CrossRef\]](#)

11. Zheng, L.; Wang, M.; Li, Y.; Xiong, Y.; Wu, C. Recycling and Degradation of Polyamides. *Molecules* **2024**, *29*, 1742. [[CrossRef](#)] [[PubMed](#)]
12. Soto-Salcido, L.A.; Pihlajamäki, A.; Mänttari, M. Reuse of end—Of—Life membranes through accelerated polyamide degradation. *Waste Manag.* **2023**, *171*, 124–133. [[CrossRef](#)] [[PubMed](#)]
13. Uddin, M.A.-O.; Williams, D.; Blencowe, A.A.-O. Recycling of Selective Laser Sintering Waste Nylon Powders into Fused Filament Fabrication Parts Reinforced with Mg Particles. *Polymers* **2021**, *13*, 2046. [[CrossRef](#)] [[PubMed](#)]
14. Al-Mazrouei, N.; Al-Marzouqi, A.H.; Ahmed, W. Characterization and Sustainability Potential of Recycling 3D-Printed Nylon Composite Wastes. *Sustainability* **2022**, *14*, 10458. [[CrossRef](#)]
15. Braun, M.; Levy, A.B.; Sifniades, S. Recycling Nylon 6 Carpet to Caprolactam. *Polym.-Plast. Technol.* **1999**, *38*, 471–484. [[CrossRef](#)]
16. Bockhorn, H.; Donner, S.; Gernsbeck, M.; Hornung, A.; Hornung, U. Pyrolysis of polyamide 6 under catalytic conditions and its application to reutilization of carpets. *J. Anal. Appl. Pyrolysis* **2001**, *58–59*, 79–94. [[CrossRef](#)]
17. Sotayo, A.; Green, S.; Turvey, G. Carpet recycling: A review of recycled carpets for structural composites. *Environ. Technol. Innov.* **2015**, *3*, 97–107. [[CrossRef](#)]
18. David Donald, J.; Dickerson Jerauld, L.; Sincok Thomas, F. Thermoplastic Composition and Method for Producing Thermoplastic Composition by Melt Blending Carpet. U.S. Patent 5294384 A, 15 March 1994.
19. Mondragon, G.; Kortaberria, G.; Mendiburu, E.; González, N.; Arbelaiz, A.; Peña-Rodriguez, C. Thermomechanical recycling of polyamide 6 from fishing nets waste. *Appl. Polym. Sci.* **2020**, *137*, 48442. [[CrossRef](#)]
20. Pan, G.; Zhao, Y.; Xu, H.; Hou, X.; Yang, Y. Compression molded composites from discarded nylon 6/nylon 6,6 carpets for sustainable industries. *J. Clean. Prod.* **2016**, *117*, 212–220. [[CrossRef](#)]
21. Lozano-González, M.J.; Rodriguez-Hernandez, M.T.; Gonzalez-De Los Santos, E.A.; Villalpando-Olmos, J. Physical–mechanical properties and morphological study on nylon-6 recycling by injection molding. *Appl. Polym. Sci.* **2000**, *76*, 851–858. [[CrossRef](#)]
22. Bernasconi, A.; Davoli, P.; Rossin, D.; Armanni, C. Effect of reprocessing on the fatigue strength of a fibreglass reinforced polyamide. *Compos. Part A Appl. Sci. Manuf.* **2007**, *38*, 710–718. [[CrossRef](#)]
23. Colucci, G.; Ostrovskaya, O.; Frache, A.; Martorana, B.; Badini, C. The effect of mechanical recycling on the microstructure and properties of PA66 composites reinforced with carbon fibers. *Appl. Polym. Sci.* **2015**, *132*, 42275. [[CrossRef](#)]
24. Pietroluongo, M.; Padovano, E.; Frache, A.; Badini, C. Mechanical recycling of an end-of-life automotive composite component. *Sustain. Mater. Technol.* **2020**, *23*, e00143. [[CrossRef](#)]
25. Lopera-Valle, A.; Wilson, P.; Coles, S.R.; Kirwan, K. Closed-loop recycling of reclaimed short carbon fibre reinforced polyamide composites. *J. Clean. Prod.* **2025**, *507*, 145546. [[CrossRef](#)]
26. La Mantia, F.P.; Curto, D.; Scaffaro, R. Recycling of dry and wet polyamide 6. *Appl. Polym. Sci.* **2002**, *86*, 1899–1903. [[CrossRef](#)]
27. Ludaš Dujmić, A.; Radičić, R.; Ercegović Ražić, S.; Cingesar, I.K.; Glogar, M.; Jurov, A.; Krstulović, N. Characterization of Melt-Spun Recycled PA 6 Polymer by Adding ZnO Nanoparticles during the Extrusion Process. *Polymers* **2024**, *16*, 1883. [[CrossRef](#)]
28. Romeiro, A.; Teixeira, C.; Costa, H.; Coelho, J.F.J.; Serra, A.C. Recycling Polyethylene/Polyamide Multilayer Films with Poly(isoprene-g-Maleic Anhydride) Compatibilizer. *Polymers* **2024**, *16*, 1079. [[CrossRef](#)]
29. Haddar, M.; Koubaa, S.; Issaoui, M.; Frikha, A. Optimization in the reprocessing of recycled polyamide 6 reinforced with 30 wt% Glass Fiber (PA6/GF30) using mixture design. *Polym. Adv. Technol.* **2024**, *35*, e6240. [[CrossRef](#)]
30. Schall, C.; Altepeter, M.; Schöppner, V.; Wanke, S.; Kley, M. Material-Preserving Extrusion of Polyamide on a Twin-Screw Extruder. *Polymers* **2023**, *15*, 1033. [[CrossRef](#)]
31. Dehghani, S.; Salehiyan, R.; Srithep, Y. Mechanical recycling of polyamide 6 and polypropylene for automotive applications. *Polym. Eng. Sci.* **2025**, *65*, 250–257. [[CrossRef](#)]
32. Ye, W.; Yuan, Y.; Liu, S.; Zhao, J. A strategy towards simultaneously improving strength and processability of polyamide 6 using bespoke dynamic covalent chain extender. *Polym. Adv. Technol.* **2024**, *35*, e6266. [[CrossRef](#)]
33. Yıldırım, R.; Mert, O.; Özkoç, G.; Kodal, M. Enhanced Recyclability of Thermoplastic Elastomer Toughened Polyamide 6 via Tri- and Multi-epoxy-Terminated POSS Hybrid Additives. *ACS Omega* **2024**, *9*, 45467–45486. [[CrossRef](#)] [[PubMed](#)]
34. Gorreta, G.; Maesani, C.; Alini, S.; Blangetti, M.; Prandi, C. Towards fiber-to-fiber recycling of synthetic textile wastes: The problem of decolorization. *Waste Manag.* **2025**, *205*, 114979. [[CrossRef](#)] [[PubMed](#)]
35. Kovács, Z.; Toldy, A. Flame Retardancy via in-Mould Coating and Durability of Flame Retardants After Mechanical Recycling in all-polyamide Composites Prepared by In Situ Polymerisation. *Macromol. Mater. Eng.* **2025**, *310*, 2400325. [[CrossRef](#)]
36. Drohsler, P.; Pummerova, M.; Hanusova, D.; Sanetrnik, D.; Foldynova, D.; Marek, J.; Martinkova, L.; Sedlarik, V. A Method for Mitigating Degradation Effects on Polyamide Textile Yarn During Mechanical Recycling. *Polymers* **2025**, *17*, 3243. [[CrossRef](#)]
37. Su, K.-H.; Lin, J.-H.; Lin, C.-C. Influence of reprocessing on the mechanical properties and structure of polyamide 6. *J. Mater. Process. Technol.* **2007**, *192–193*, 532–538. [[CrossRef](#)]
38. Li, G.; Ma, S.; Szostak, M. Amide Bond Activation: The Power of Resonance. *Trends Chem.* **2020**, *2*, 914–928. [[CrossRef](#)]
39. Schroeder, L.R.; Cooper, S.L. Hydrogen bonding in polyamides. *J. Appl. Phys.* **1976**, *47*, 4310–4317. [[CrossRef](#)]

40. Klun, U.; Kržan, A. Rapid microwave induced depolymerization of polyamide-6. *Polymer* **2000**, *41*, 4361–4365. [\[CrossRef\]](#)
41. Češarek, U.; Pahovnik, D.; Žagar, E. Chemical Recycling of Aliphatic Polyamides by Microwave-Assisted Hydrolysis for Efficient Monomer Recovery. *ACS Sustain. Chem. Eng.* **2020**, *8*, 16274–16282. [\[CrossRef\]](#)
42. Yuan, X.-X.; Zhou, Q.; Li, X.-Y.; Yang, P.; Yang, K.-K.; Wang, Y.-Z. Degradation of nylon 6 to produce a “pseudo” amino acid ionic liquid. *Polym. Degrad. Stab.* **2014**, *109*, 171–174. [\[CrossRef\]](#)
43. Meng, L.; Zhang, Y.; Huang, Y.; Shibata, M.; Yosomiya, R. Studies on the decomposition behavior of nylon-66 in supercritical water. *Polym. Degrad. Stab.* **2004**, *83*, 389–393. [\[CrossRef\]](#)
44. Wang, W.; Meng, L.; Huang, Y. Hydrolytic degradation of monomer casting nylon in subcritical water. *Polym. Degrad. Stab.* **2014**, *110*, 312–317. [\[CrossRef\]](#)
45. Iwaya, T.; Sasaki, M.; Goto, M. Kinetic analysis for hydrothermal depolymerization of nylon 6. *Polym. Degrad. Stab.* **2006**, *91*, 1989–1995. [\[CrossRef\]](#)
46. Mukherjee, A.K.; Goel, D.K. Depolymerization of poly-ε-caprolactam catalyzed by sodium hydroxide. *Appl. Polym. Sci.* **1978**, *22*, 361–368. [\[CrossRef\]](#)
47. Bonfield John, H.; Hecker Richard, C.; Snider Orvill, E.; Apostle Basil, G. Regeneration of ε-Caprolactam from Polyamides. U.S. Patent 3182055 A, 4 May 1965.
48. Fuchs, H.; Neubauer, G.; Ritz, J.; Priester, C.-U. Recovery of Caprolactam from Polycaprolactam. U.S. Patent 5359062 A, 25 October 1994.
49. Wursthorn, L.; Beckett, K.; Rothbaum, J.O.; Cywar, R.M.; Lincoln, C.; Kratish, Y.; Marks, T.J. Selective Lanthanide-Organic Catalyzed Depolymerization of Nylon-6 to ε-Caprolactam. *Angew. Chem. Int. Ed.* **2023**, *62*, e202212543. [\[CrossRef\]](#)
50. Chen, X.-H.; Wu, G.; Chen, S.-C.; Wang, Y.-Z. Facile, high-efficiency, and low-cost depolymerization of PA6 to ε-caprolactam enables closed-loop chemical recycling. *Polymer* **2023**, *283*, 126201. [\[CrossRef\]](#)
51. Chen, H.; Yang, R.; Dong, B.; Sun, H.; Xu, G.; Wang, Q. Closed-loop recycling of Nylon-6 to Caprolactam catalyzed by a green and effective phosphazene base. *J. Polym. Sci.* **2024**, *62*, 5609–5617. [\[CrossRef\]](#)
52. Ye, L.; Liu, X.; Beckett, K.B.; Rothbaum, J.O.; Lincoln, C.; Broadbelt, L.J.; Kratish, Y.; Marks, T.J. Catalyst metal-ligand design for rapid, selective, and solventless depolymerization of Nylon-6 plastics. *Chem* **2024**, *10*, 172–189. [\[CrossRef\]](#)
53. Kumar, A.; von Wolff, N.; Rauch, M.; Zou, Y.-Q.; Shmul, G.; Ben-David, Y.; Leituss, G.; Avram, L.; Milstein, D. Hydrogenative Depolymerization of Nylons. *J. Am. Chem. Soc.* **2020**, *142*, 14267–14275. [\[CrossRef\]](#)
54. Niu, Z.; Hu, Q. Ruthenium Monatomic Alloy Catalyst and Plastic Hydrogenolysis Method. CN 119869514 A, 25 April 2025.
55. Lin, B.; Qiu, Z.; Chen, Z. Catalyst, Preparation Method and Application Thereof, and Catalytic Hydrogenolysis Method. CN 117000287 A, 11 November 2025.
56. Duch, M.W.; Allgeier, A.M. Deactivation of nitrile hydrogenation catalysts: New mechanistic insight from a nylon recycle process. *Appl. Catal. A Gen.* **2007**, *318*, 190–198. [\[CrossRef\]](#)
57. Coeck, R.; De Bruyne, A.; Borremans, T.; Stuyck, W.; De Vos, D.E. Ammonolytic Hydrogenation of Secondary Amides: An Efficient Method for the Recycling of Long-Chain Polyamides. *ACS Sustain. Chem. Eng.* **2022**, *10*, 3048–3056. [\[CrossRef\]](#)
58. Stuyck, W.; Janssens, K.; Denayer, M.; De Schouwer, F.; Coeck, R.; Bernaerts, K.V.; Vekeman, J.; De Proft, F.; De Vos, D.E. A sustainable way of recycling polyamides: Dissolution and ammonolysis of polyamides to diamines and diamides using ammonia and biosourced glycerol. *Green Chem.* **2022**, *24*, 6923–6930. [\[CrossRef\]](#)
59. McKinney Ronald, J. Ammonolysis of Nylon. U.S. Patent 5302756 A, 12 April 1994.
60. Kim, K.J.; Dhevi, D.M.; Lee, J.S.; Cho, Y.D.; Choe, E.K. Mechanism of glycolysis of nylon 6,6 and its model compound by ethylene glycol. *Polym. Degrad. Stab.* **2006**, *91*, 1545–1555. [\[CrossRef\]](#)
61. Datta, J.; Błażek, K.; Włoch, M.; Bukowski, R. A New Approach to Chemical Recycling of Polyamide 6.6 and Synthesis of Polyurethanes with Recovered Intermediates. *J. Polym. Environ.* **2018**, *26*, 4415–4429. [\[CrossRef\]](#)
62. Kamimura, A.; Oishi, Y.; Kaiso, K.; Sugimoto, T.; Kashiwagi, K. Supercritical Secondary Alcohols as Useful Media to Convert Polyamide into Monomeric Lactams. *ChemSusChem* **2008**, *1*, 82–84. [\[CrossRef\]](#)
63. Kamimura, A.; Kaiso, K.; Suzuki, S.; Oishi, Y.; Ohara, Y.; Sugimoto, T.; Kashiwagi, K.; Yoshimoto, M. Direct conversion of polyamides to ω-hydroxyalkanoic acid derivatives by using supercritical MeOH. *Green Chem.* **2011**, *13*, 2055–2061. [\[CrossRef\]](#)
64. Kawetirawatt, T.; Yamaguchi, T.; Hayashiyama, S.; Sumimoto, M.; Kamimura, A.; Hori, K. Nylon 6 depolymerization in supercritical alcohols studied by the QM/MC/FEP method. *RSC Adv.* **2012**, *2*, 8402–8409. [\[CrossRef\]](#)
65. Kamimura, A.; Ikeda, K.; Suzuki, S.; Kato, K.; Akinari, Y.; Sugimoto, T.; Kashiwagi, K.; Kaiso, K.; Matsumoto, H.; Yoshimoto, M. Efficient Conversion of Polyamides to ω-Hydroxyalkanoic Acids: A New Method for Chemical Recycling of Waste Plastics. *ChemSusChem* **2014**, *7*, 2473–2477. [\[CrossRef\]](#)
66. Kamimura, A.; Sugimoto, T.; Kaiso, K. Method of Depolymerizing Polyamides and Method of Manufacturing Polyamide Monomers. EP 1801101 A1, 11 January 2009.
67. Goto, M.; Sasaki, M.; Hirose, T. Reactions of polymers in supercritical fluids for chemical recycling of waste plastics. *J. Mater. Sci.* **2006**, *41*, 1509–1515. [\[CrossRef\]](#)

68. Meng, C.; Wu, Y.; Wang, R.; Zhang, S.; Ji, P.; Wang, C.; Wang, H. Efficient hydrolytic recycling of PA6 supported by kinetic modeling. *Polym. Degrad. Stab.* **2025**, *233*, 111178. [\[CrossRef\]](#)
69. Shukla, S.R.; Harad, A.M.; Mahato, D. Depolymerization of nylon 6 waste fibers. *Appl. Polym. Sci.* **2006**, *100*, 186–190. [\[CrossRef\]](#)
70. Khuntia, S.P.; Gadgeel, A.; Mestry, S.; Mhaske, S.T. Organo-sulfonic acid catalyzed degradation kinetics and thermodynamic studies of nylon-6 by hydrothermal method. *Polym. Adv. Technol.* **2022**, *33*, 411–426. [\[CrossRef\]](#)
71. Bäckström, E.; Odelius, K.; Hakkarainen, M. Microwave Assisted Selective Hydrolysis of Polyamides from Multicomponent Carpet Waste. *Glob. Chall.* **2021**, *5*, 2000119. [\[CrossRef\]](#)
72. Yi, X.; Li, Y.; Liu, M.; Peng, X.; Wang, X.; Yi, C. Efficient Hydrolytic Degradation of Polyamide 6 Using a Recyclable Solid Phosphoric Acid Catalyst. *ACS Appl. Polym. Mater.* **2025**, *7*, 8234–8244. [\[CrossRef\]](#)
73. Jiang, Y.; Feng, B.; Gao, Y.; Liu, X.; Wang, Y. Efficient recycling of polyamide 6 to ϵ -caprolactam under mild conditions. *Catal. Today* **2025**, *456*, 115344. [\[CrossRef\]](#)
74. Minor, A.-J.; Goldhahn, R.; Rihko-Struckmann, L.; Sundmacher, K. Chemical Recycling Processes of Nylon 6 to Caprolactam: Review and Techno-Economic Assessment. *Chem. Eng. J.* **2023**, *474*, 145333. [\[CrossRef\]](#)
75. Chaloner, P.A. Hydrogenation Methods: Paul N. Rylander, Academic Press, London, New York, 1985, xv + 193 pages, £40. ISBN 0126053650. *J. Organomet. Chem.* **1986**, *301*, C67–C68. [\[CrossRef\]](#)
76. Zhou, W.; Neumann, P.; Al Batal, M.; Rominger, F.; Hashmi, A.S.K.; Schaub, T. Depolymerization of Technical-Grade Polyamide 66 and Polyurethane Materials through Hydrogenation. *ChemSusChem* **2021**, *14*, 4176–4180. [\[CrossRef\]](#)
77. McKinney Ronald, J. Lewis Acid Catalyzed Ammonolysis of Nylon. U.S. Patent 5395974 A, 7 March 1995.
78. Feng, Y.; Quan, X.; Wang, Q.; Zhang, Y.; Liu, C.; Yuan, X.; Zhao, S.; Yang, J.; He, W.; Guo, K. Recent Advances in the Chemical Recycling of Polyamide for a Sustainable Circular Economy. *Ind. Eng. Chem. Res.* **2025**, *64*, 2516–2530. [\[CrossRef\]](#)
79. Deligeorgiev, T.; Gadjev, N.; Vasilev, A.; Drexhage, K.-H.; Yarmoluk, S.M. Synthesis of novel monomeric and homodimeric cyanine dyes with thioacetyl substituents for nucleic acid detection. *Dye. Pigment.* **2007**, *72*, 28–32. [\[CrossRef\]](#)
80. Coffey, J.L.; Johnson, M.A.; Zhang, L.; Wells, R.L.; Janik, J.F. Influence of Precursor Route on the Photoluminescence of Bulk Nanocrystalline Gallium Nitride. *Chem. Mater.* **1997**, *9*, 2671–2673. [\[CrossRef\]](#)
81. Yu, Y.; Li, X.; Krishna, R.; Liu, Y.; Cui, Y.; Du, J.; Liang, Z.; Song, X.; Yu, J. Enhancing CO₂ Adsorption and Separation Properties of Aluminophosphate Zeolites by Isomorphous Heteroatom Substitutions. *ACS Appl. Mater. Interfaces* **2018**, *10*, 43570–43577. [\[CrossRef\]](#) [\[PubMed\]](#)
82. Hao, J.H.; Chen, C.; Li, L.; Yu, L.; Jiang, W. Preparation of solvent-resistant anion-exchange membranes. *Desalination* **2000**, *129*, 15–22. [\[CrossRef\]](#)
83. Tang, M.; Shen, J.; Zhang, F.; Zhao, Y.; Gan, T.; Zeng, W.; Li, R.; Wang, D.; Han, B.; Liu, Z. Upcycling of Polyamide Wastes to Tertiary Amines Using Mo Single Atoms and Rh Nanoparticles. *Angew. Chem. Int. Ed.* **2025**, *64*, e202416436. [\[CrossRef\]](#)
84. Yang, J.; Wang, Y.; Fan, Y.; Xu, B.; Tu, T. Sustainable recycling of polyamides via C–N bond cleavage facilitated by methyl tosylate under mild conditions. *Nat. Commun.* **2025**, *16*, 8884. [\[CrossRef\]](#)
85. Liu, S.-Z.; Liu, W.-H.; Deng, Y.; Li, Q.; Dou, M.-Y.; Cui, Y.; Dou, J.-M. HBF₄-mediated direct alcoholysis of amides under mild conditions. *Org. Chem. Front.* **2025**, *12*, 5438–5444. [\[CrossRef\]](#)
86. Kubicki, S.; Bator, I.; Jankowski, S.; Schipper, K.; Tiso, T.; Feldbrügge, M.; Blank, L.M.; Thies, S.; Jaeger, K.-E. A Straightforward Assay for Screening and Quantification of Biosurfactants in Microbial Culture Supernatants. *Front. Bioeng. Biotechnol.* **2020**, *8*, 958. [\[CrossRef\]](#)
87. Rodrigues, A.L.; Göcke, Y.; Bolten, C.; Brock, N.L.; Dickschat, J.S.; Wittmann, C. Microbial production of the drugs violacein and deoxyviolacein: Analytical development and strain comparison. *Biotechnol. Lett.* **2012**, *34*, 717–720. [\[CrossRef\]](#)
88. de Witt, J.; Luthe, T.; Wiechert, J.; Jensen, K.; Polen, T.; Wirtz, A.; Thies, S.; Frunzke, J.; Wynands, B.; Wierckx, N. Upcycling of polyamides through chemical hydrolysis and engineered *Pseudomonas putida*. *Nat. Microbiol.* **2025**, *10*, 667–680. [\[CrossRef\]](#)
89. Lan, J.; Deng, C.; Zhao, Z.-Y.; Wang, Y.-Z. An upcycling strategy for polyamide 6: Preparing thermoplastic polyamide elastomers from glycolysates produced by controlled degradation. *Green Chem.* **2025**, *27*, 1183–1193. [\[CrossRef\]](#)
90. Tian, Z.; Shao, X.; Zhang, J.; Su, L.; Wang, Y.; Deng, T.; Wang, Y.; Hou, X. Chemical recycling of waste poly-p-phenylene terephthamide via selective cleavage of amide bonds catalyzed by strong Brønsted base in alcohols. *Waste Manag.* **2022**, *137*, 275–282. [\[CrossRef\]](#) [\[PubMed\]](#)
91. Cywar, R.M.; Rorrer, N.A.; Mayes, H.B.; Maurya, A.K.; Tassone, C.J.; Beckham, G.T.; Chen, E.Y.X. Redesigning Hybrid Nylons with Optical Clarity and Chemical Recyclability. *J. Am. Chem. Soc.* **2022**, *144*, 5366–5376. [\[CrossRef\]](#) [\[PubMed\]](#)
92. Shiraki, R.; Hsu, Y.-I.; Uyama, H.; Tobisu, M. Synthesis of Polyamides Bearing Directing Groups and Their Catalytic Depolymerization. *Org. Lett.* **2025**, *27*, 1453–1458. [\[CrossRef\]](#)
93. He, F.-M.; Xiao, Y.-F.; Zhang, Q.; Jiang, M.; Li, X.; Guo, D.-M.; Chen, L.; Liu, B.-W.; Wang, Y.-Z. Functional design of caprolactam for aliphatic polyamide with enhanced flame retardancy, mechanical robustness, and chemical recyclability. *Chem. Eng. J.* **2025**, *505*, 159551. [\[CrossRef\]](#)

94. Chen, J.-H.; Tu, Y.-M.; Yao, J.-R.; Tang, X.-T.; Xia, Y.-Y.; Cai, Z.; Zhang, Q.; Zhu, J.-B. Accessing chemically recyclable polyamides via geminal dimethyl substitution. *Polymer* **2024**, *298*, 126898. [\[CrossRef\]](#)
95. Chen, J.; Luo, K.; Zhu, J.; Yu, J.; Wang, Y.; Hu, Z. Reversibly cross-linked fullerene/polyamide composites based on Diels-Alder reaction. *Compos. Sci. Technol.* **2019**, *176*, 9–16. [\[CrossRef\]](#)
96. Ding, H.; Jing, C.; Guo, C.; Zhu, T.; Zhang, K. Closed-Loop Chemical Recycling of Polyamide Thermosets via Reversible Amidation. *Macromolecules* **2025**, *58*, 6480–6487. [\[CrossRef\]](#)
97. Lu, W.; Zhu, P.; Zhao, Y.; Wang, D.; Dong, X. A Transparent, Healable and Recyclable Alicyclic Poly(ether-b-amide) Multiblock Copolymer with Ultrahigh Toughness. *Chem.–Eur. J.* **2023**, *29*, e202300622. [\[CrossRef\]](#)
98. Xie, P.; Lu, X.; Li, X.; Wen, X.; Sun, J. Mass-Produced Chemically Recyclable Aromatic Polymers with Exceptional Strength and Stability. *ACS Macro Lett.* **2025**, *14*, 735–742. [\[CrossRef\]](#)
99. Lv, W.; Li, M.; Tao, Y. Bridged Bicyclic Lactam Enables Chemically Recyclable Nylon. *Angew. Chem. Int. Ed.* **2024**, *63*, e202402541. [\[CrossRef\]](#) [\[PubMed\]](#)
100. Kawasaki, N.; Yamano, N.; Nakayama, A. Synthesis, properties, and biodegradability of three-branched copolyamide (4/6). *Appl. Polym. Sci.* **2020**, *137*, 49165. [\[CrossRef\]](#)
101. Kawasaki, N.; Yamano, N.; Nakayama, A. Synthesis of N-methylol polyamide 4: Characterization, properties, and biodegradability. *Mater. Adv.* **2024**, *5*, 240–248. [\[CrossRef\]](#)
102. Tang, X.-T.; Zhou, J.-A.-Q.; Tu, Y.-M.; Fan, H.-Z.; Wang, M.-Y.; Cao, Q.; Cai, Z.; Zhu, J.-B. Ring-Opening Polymerization Enables Access to High-Performance Aliphatic-Aromatic Polyamides with Chemical Recyclability. *Angew. Chem. Int. Ed.* **2025**, *64*, e202505310. [\[CrossRef\]](#)
103. Bell, E.L.; Rosetto, G.; Ingraham, M.A.; Ramirez, K.J.; Lincoln, C.; Clarke, R.W.; Gado, J.E.; Lilly, J.L.; Kucharzyk, K.H.; Erickson, E.; et al. Natural diversity screening, assay development, and characterization of nylon-6 enzymatic depolymerization. *Nat. Commun.* **2024**, *15*, 1217. [\[CrossRef\]](#)
104. Shiraishi, Y.; Kato, D.-i.; Miyazaki, K.; Yonemura, M.; Furuno, Y.; Yokoyama, R.; Yokogawa, Y.; Nonaka, S.; Kaneko, Y.; Ebata, K.; et al. Quantitative nylon monomerization by the combination of chemical pretreatment and enzymatic hydrolysis using nylon hydrolases. *PLoS ONE* **2025**, *20*, e0318641. [\[CrossRef\]](#)
105. Li, W.; Du, S.; Han, D.; Wu, S. Measurement and Correlation of the Solubility of Aminocaproic Acid in Some Pure and Binary Solvents. *J. Chem. Eng. Data* **2019**, *64*, 5312–5323. [\[CrossRef\]](#)
106. Tonsi, G.; Maesani, C.; Ortenzi, M.A.; Alini, S.; Pirola, C. The selective dissolution-precipitation recycling: A review on this alternative approach for the recovery of nylon-based waste materials. *Waste Manag.* **2025**, *204*, 114937. [\[CrossRef\]](#)
107. Tonsi, G.; Caccia, M.; Maesani, C.; Simon Ostan, P.; Ortenzi, M.A.; Alini, S.; Pirola, C. Polyamide recycling by selective dissolution approach: Life Cycle Assessment study and environmental impacts comparison with different recycling technologies. *Polym. Eng. Sci.* **2025**, *65*, 765–782. [\[CrossRef\]](#)
108. Tanks, J.; Tamura, K. Room-Temperature Material Recycling/Upcycling of Polyamide Waste Enabled by Cosolvent-Tunable Dissolution Kinetics. *Angew. Chem. Int. Ed.* **2025**, *64*, e202502474. [\[CrossRef\]](#)
109. Rietzler, B.; Manian, A.P.; Rhomberg, D.; Bechtold, T.; Pham, T. Investigation of the decomplexation of polyamide/CaCl₂ complex toward a green, nondestructive recovery of polyamide from textile waste. *Appl. Polym. Sci.* **2021**, *138*, 51170. [\[CrossRef\]](#)
110. Manian, A.P.; Kraegeloh, F.E.; Braun, D.E.; Mahmud-Ali, A.; Bechtold, T.; Pham, T. Separation of polyamide 66 from mixtures with cellulose fibers by selective dissolution in calcium chloride-ethanol-water solvent. *Appl. Polym. Sci.* **2023**, *140*, e53813. [\[CrossRef\]](#)
111. Ye, L.; Liu, X.; Beckett, K.; Rothbaum, J.; Lincoln, C.; Broadbelt, L.; Kratish, Y.; Marks, T. Catalyst Design to Address Nylon Plastics Recycling. *ChemRxiv* **2023**. [\[CrossRef\]](#)

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