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Advanced technologies for plastic waste recycling: examine recent developments in plastic waste recycling technologies

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The escalating challenge of plastic waste necessitates innovative strategies that surpass conventional mechanical recycling. This review examines recent advancements in plastic waste recycling technologies, with a focus on three primary domains: chemical recycling, biological degradation, and enhanced sorting techniques. Chemical recycling employs depolymerization and pyrolysis to dismantle heterogeneous polymers into recoverable monomers, mitigating the constraints of mechanical methods on mixed waste streams. Biological approaches utilize enzymes and microbial consortia for environmentally benign degradation, with emerging engineered variants demonstrating efficacy across diverse polymer types. Furthermore, the integration of artificial intelligence (AI) in sorting systems enhances separation accuracy and throughput by up to 95%. Collectively, these developments foster a robust, sustainable recycling infrastructure aligned with circular economy principles. Nonetheless, barriers such as technological scalability, economic viability, and process optimization persist. This analysis evaluates these innovations' potential to elevate recycling rates, minimize ecological harm, and promote material circularity, while delineating principal obstacles and priority areas for future investigation to facilitate commercial deployment.

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1. Introduction

1.1 Background

The escalating dependence on plastics has precipitated a profound environmental crisis, with profound implications for human health and ecosystems. From 1950 to 2015, global production reached 8300 million metric tonnes (Mt) of plastics, of which merely 9% underwent recycling.[1] Approximately 12.7 million Mt of plastic waste entered oceans in 2010, a volume projected to increase tenfold by 2025 absent enhanced management practices.[2] Mismanaged waste such as litter, open dumping, or unregulated landfilling facilitates ingress into natural environments.[3] Over 80% of marine plastic pollution originates from terrestrial sources, underscoring deficiencies in waste governance.[4] Environmental fragmentation yields micro- and nanoplastics, disseminated *via* fluvial, oceanic, and atmospheric pathways. These particulates bioaccumulate across trophic levels, impairing marine biodiversity, and enter human diets, with estimates suggesting weekly ingestion of 0.1–5 g per individual equivalent to a credit card at the upper bound.[5] Although the health ramifications remain incompletely elucidated, accumulating evidence implicates microplastics in pathogen vectoring, alongside toxicity from inherent additives, sorbed contaminants, or polymer particulates *via* ingestion or inhalation.[6]

Urgent remediation of plastic mismanagement is imperative to safeguard ecosystems and public health. The Global Plastic Waste Management System (GPWMS) constitutes an intricate, interdependent network wherein component inputs and outputs exert reciprocal influences. Fundamentally, the GPWMS encompasses three phases: initial waste generation (IWG), intermediate handling (including collection, recycling, and the Plastic Waste Trade Network [PWTN]), and terminal disposal (*e.g.*, landfilling, incineration, or uncontrolled release).[7] Recycling encompassing collection, material recovery, and reprocessing varies by jurisdiction and technology, yet garners substantial scholarly and policy emphasis as a cornerstone of circular economies.[8] Notwithstanding, empirical recycling stands at 9%, with scant evidence of displacement of virgin production.[9] Displacement efficacy, defined as the quantity of virgin material averted per unit of recyclate, proves elusive due to economic volatilities, behavioral factors, and counterfactual estimation challenges.[10]

Recycling entails a sequential cascade susceptible to attrition at each juncture. While extant technologies augment efficacy, their aggregate potential to curtail virgin waste generation (VWG)

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remains underexplored.[11] Emerging chemical recycling modalities promise near-indefinite loops with minimal quality degradation[12] Quantifying inter-stage synergies could inform investment prioritization, while idealized GPWMS modeling elucidates systemic ceilings.[13] evaluated sorting and reprocessing efficiencies across European recycling plants and material recovery facilities (MRFs), synthesizing prior literature with proprietary operational data to quantify material recovery rates (*e.g.*, 75–90% for PET streams). Similarly,[14] conducted a life cycle assessment (LCA) contrasting environmental burdens of chemical (pyrolysis-based) *versus* mechanical recycling, revealing the former's 50% reduction in climate change impacts relative to energy recovery, albeit with elevated energy demands. Material flow modeling of U.S. PET cycles (incorporating trade dynamics), underscore recycling's prospective yet constrained role.[10]

The PWTN has faced intensified scrutiny since China's 2018 import prohibition, which curtailed its 50% share of global flows.[15] Redirected exports to Southeast Asia prompted reciprocal bans in Malaysia, Vietnam, and Thailand.[4] Predominantly unidirectional from affluent, infrastructure-rich nations to developing economies with lax regulations this trade perpetuates inequities, amplifying pollution in recipient locales.[16] Quantifying PWTN contributions to mismanagement eludes precise metrics, contingent on counterfactuals (*e.g.*, domestic recycling *versus* landfilling) and capacity displacements.[17]

Network analyses[18] delineate structures but omit impacts; post-ban LCAs[19] and emission models[20] forecast 111 Mt redirected by 2030.[14] This review simulates GPWMS perturbations *via* PWTN elimination (scenarios T.1–T.4) and recycling enhancements (R.1–R.5), assessing equity burdens and "infinite" recycling viability.[17,21–23] Outcomes inform exporter preparedness and policy formulation, circumscribing recycling's standalone efficacy without production curbs.[24]

1.2 Importance of plastic waste recycling

Over the past 70 years, plastics have become incredibly common in all sorts of structural and non-structural uses, catching the eye of many industries. However, a major problem is that most plastics made in the last 60 years don't break down naturally and can take decades to decompose.[25] With a staggering 86% of plastics ending up in landfills,[20] a huge amount of plastic waste has built up over time, creating waste management headaches and environmental problems, like microplastics polluting oceans and being ingested by humans and animals.[25] A big reason for this mess is the heavy reliance on plastics meant to be thrown away after just one use. Instead of being single-use, plastics could be recycled to make the most of the energy already used to produce and distribute them.[26] That's why it's so important for designers to think about recycling and create products that can be reused in ways different from their original purpose. Just to clarify, in this paper, we use "thermoplastics" and "plastics" interchangeably to refer only to polymers that can be melted and reshaped.

Plastic waste poses major hurdles for effective recycling. In the US, plastics account for about 12.9% of all municipal solid waste.[27] Unlike metals, which are relatively easy to recycle, plastics present unique challenges. They're used in a wide range of products, with packaging and single-use items making up roughly half of all plastic applications. Only about 20% to 25% of plastics are used in long-lasting structures, mostly in construction and building, while the rest go into medium-term products like electronics, furniture, vehicles, and agricultural items.[28] Plastic production includes various types: polyethylene (PE) makes up 24%, polypropylene (PP) 16.6%, polyvinyl chloride (PVC) 11.4%, polyurethane (PU) 5.5%, polystyrene (PS) 6.1%, and polyethylene terephthalate (PET) 5.3%.[1] The mix of different plastics, combined with contamination from things like food scraps, metal, paper, pigments, or ink, makes recycling trickier. Limited collection and sorting systems, the difficulty of accurately separating plastic types, and the high costs of collecting and processing plastic waste only add to the problem.

The steep costs of recycling discourage both manufacturers and investors, creating a major roadblock to widespread recycling programs. Recycling and reusing plastics can cut carbon emissions by 30% to 80% compared to making new plastics.[2] As governments start implementing carbon pricing, recycling could become more financially appealing than producing new plastics. To make recycled plastics competitive with virgin materials and improve their quality, significant investment in recycling technologies is crucial. Environmental factors like UV radiation, oxygen, and heat speed up plastic degradation, which complicates recycling efforts and lowers the quality of recycled plastics. Compared to virgin plastics, recycled plastics often have issues like inconsistent color and reduced strength, making them less appealing to manufacturers and limiting their use in new products.[3] These quality issues call for more research and attention to improve the usability and appeal of recycled plastics across industries.

Plastic recycling falls into four categories: primary, secondary, tertiary, and quaternary. Each has its own processes and goals. Primary recycling, or closed-loop recycling, mechanically reprocesses plastic waste to create products with qualities similar to the original material. Secondary recycling, or downgrading, mechanically reprocesses waste into products with different properties. Tertiary recycling focuses on recovering chemical components from plastics, while quaternary recycling harnesses the energy in plastic waste to generate steam or electricity.[4] Mechanical recycling is used in both primary and secondary processes. Most thermoplastics, like PET, PE, and PP, are well-suited for mechanical recycling, but thermosets, such as unsaturated polyester and epoxy resin, can't be recycled this way due to their molecular structure. The different processing needs and molecular mismatches among plastic types make it tough to produce recycled plastic from waste. Mechanical recycling involves key steps like collecting, sorting, washing, shredding, and compatibilization or separation. These steps typically happen at large recycling facilities located near industrial or urban areas, equipped with advanced machinery to handle big volumes of plastic waste efficiently.[5]

1.3 Objectives of the review

Since 1950, over 90% of plastic products have ended up in landfills, been incinerated, or released into the environment, reflecting the "take-make-waste" model of the linear economy. To meet ambitious targets set by the U.S. Plastics Pact and the European Union for recycling or composting 50% of plastic packaging by 2025, advancements in recycling are essential.[6] New recycling methods, both closed-loop (turning plastic back into plastic) and open-loop (converting plastic into other materials), are being developed and can be grouped into physical and chemical approaches. Physical recycling keeps the plastic's molecular structure intact through processes like mechanical recycling or solvent-based methods. Chemical recycling, on the other hand, breaks plastics down into their basic building blocks, using techniques like glycolysis, methanolysis, or hydrolysis to convert polymers with heteroatoms into monomers or oligomers, or high-temperature processes like pyrolysis and gasification to transform plastics into fuels or chemical feedstocks. Given the vast scope of plastic recycling research, figuring out how to apply these technologies in a way that's both cost-effective and environmentally friendly to create a circular system for plastics is no easy task.[7] Tools like techno-economic analysis (TEA) and life cycle assessment (LCA) are used to evaluate the costs and environmental impacts of recycling methods, but differences in assumptions and data make it hard to compare technologies fairly. This study uses a comprehensive modeling approach to assess both current and emerging plastic recycling technologies. We focus on closed-loop recycling of common plastics like high- and low-density polyethylene (HDPE and LDPE), polyethylene terephthalate (PET), and polypropylene (PP), using methods like mechanical recycling, solvent-based dissolution, glycolysis, methanolysis, and enzymatic hydrolysis of PET (Fig. 1). By combining literature reviews, Aspen Plus modeling, the Materials Flows through Industry (MFI) tool, and process-based LCA,[8] we evaluate these technologies based on technical factors (like material quality, retention, circularity, contamination tolerance, and technology readiness), environmental impacts (such as greenhouse gas emissions, energy use, land use, toxicity, waste generation, and water consumption), and economic factors (like the minimum selling price for 1 kg of recycled material). We identify key factors affecting these metrics, use them to create sensitivity analyses, perform multicriteria decision analysis (MCDA), and suggest future research directions to improve the feasibility of these technologies. This study lays the groundwork for understanding the current and future landscape of plastic recycling and provides a framework for evaluating new recycling technologies as they emerge.[9]

2. Overview of plastic waste and recycling challenges

Plastics, unlike traditional materials like paper, glass, or metals, have versatile properties that make them invaluable across industries like automotive, agriculture, electronics, packaging, and healthcare. For example, using plastics in car components reduces vehicle weight and boosts fuel efficiency.[10] Our growing reliance on the convenience of plastics has driven up global production and use, leading to massive plastic waste accumulation and widespread pollution. However, the appeal of plastics is waning due to its harmful effects on the environment and human health. Globally, over 9200 million metric tonnes (Mt) of plastic have been produced so far, with around 6900 Mt left unrecycled, piling up in landfills or littering the environment. This represents a missed economic opportunity and serious damage to ecosystems. To ensure the sustainability of this multi-billion-dollar material, we must tackle the challenges of plastic waste and adopt creative solutions to redesign plastic products with a focus on sustainability and end-of-life (EoL) management. Current

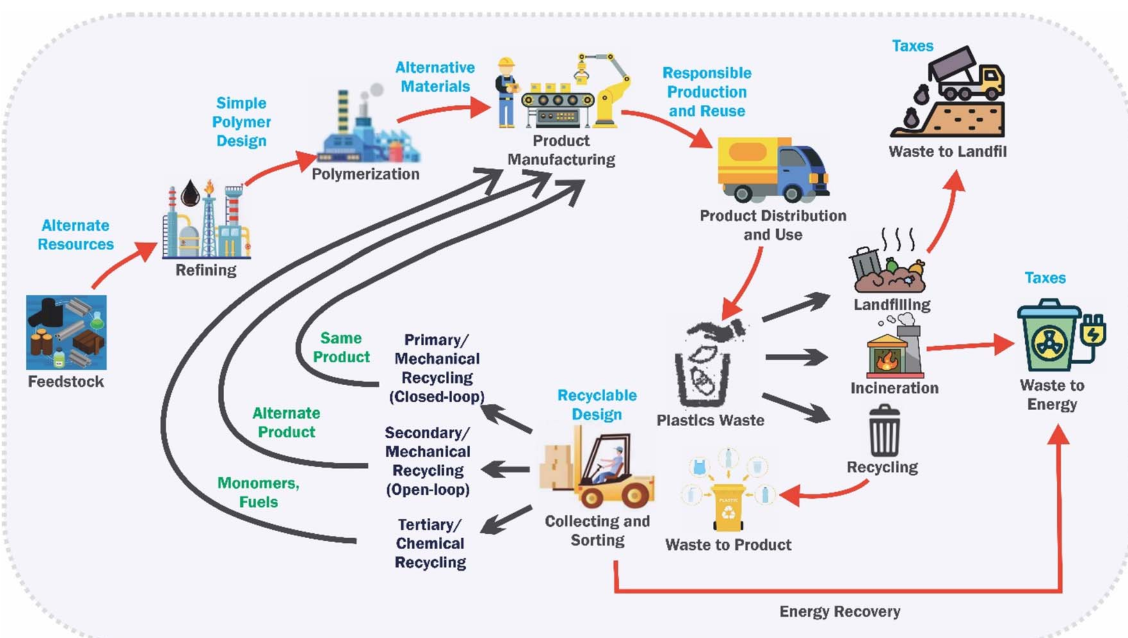

Fig. 1 Schematic showing the plastic life cycle.

approaches to handling plastic waste include: (1) landfilling, which is limited by space and risks leaking toxic substances into ecosystems, (2) waste-to-energy incineration, which can release harmful chemicals like dioxins and furans, and (3) recycling plastic waste into new products[11] (Fig. 1). Plastic waste piling up in landfills represents both a missed economic opportunity and significant environmental harm. While burning plastics for energy is a simpler option that skips the labor-intensive sorting required for recycling, it only generates limited energy and contributes to air pollution and climate change. However, emerging carbon capture technologies could help cut down CO_2 emissions from this process. On the other hand, recycling offers a promising way to address the mounting global plastic waste problem. It involves the full process of collecting waste and turning it into useful products (Fig. 1). Plastics can be recycled mechanically, keeping their original chemical structure, or chemically, altering their makeup on purpose. Right now, mechanical recycling is the most common approach, with polyethylene (PE) and polyethylene terephthalate (PET) being the most commonly recycled and valuable plastics worldwide.[12] Recycling happens through various methods, including primary, secondary, tertiary, and quaternary processes. A small share of mechanically recycled plastics goes through closed-loop recycling, creating products identical to the original, which falls under primary recycling. This method relies on high-quality waste, often from pre-consumer manufacturing scraps. Meanwhile, open-loop recycling transforms plastics into products for different uses, serving new markets.[13]

Open-loop mechanical recycling can open the door to secondary recycling opportunities. On the other hand, tertiary or chemical recycling uses methods like pyrolysis and gasification to break down plastics into their basic building blocks, such as monomers and hydrocarbons. While chemical recycling works well for mixed plastic waste, it's limited by its high energy needs and intense processing conditions. A major hurdle for technologies like gasification or pyrolysis is the need to purify the resulting materials to protect equipment and ensure the output's quality.[14] Meanwhile, quaternary recycling focuses on burning mixed plastic waste for energy recovery as an alternative to dumping it in landfills. In theory, most plastics can be recycled, and some are well-suited for a cradle-to-cradle lifecycle, supporting the idea of a circular plastic economy. However, recycling faces several challenges: the complexity of plastic products, economic factors that make virgin plastics from fossil fuels cheaper than recycled materials, harmful environmental and social impacts, and inconsistent global policies, like the Global Plastics Treaty, which guide efforts for effective closed-loop recycling.[15] To tackle the growing plastic waste issue, we support focusing on cutting down plastic production and use while exploring sustainable alternative materials.

2.1 Key challenges in plastic waste management: technical, economic, and environmental barriers

Plastics' versatility has fueled their ubiquity across sectors like packaging (50% of use), automotive, and agriculture, yet this has amplified waste accumulation: over 9,200 million metric tonnes (Mt) produced globally, with ~6,900 Mt unrecycled in landfills or environments.[11] Current management landfilling (space-constrained, leachate risks), incineration (dioxin emissions), and recycling (Fig. 1) falls short, as global recycling rates stagnate below 10% despite surging production (>400 Mt per year, half single-use),[16] as shown in Fig. 2. Thermoplastics (*e.g.*, PE 24%, PP 16.6%) dominate recyclability, but thermosets (one-third of production) and composites resist due to cross-linked structures.[19] Addressing these requires tackling intertwined technical, economic, and environmental hurdles.

2.1.1 Technical barriers: sorting, processing, and material complexity. End-of-life (EoL) plastics demand precise sorting, yet contamination from residues, additives (*e.g.*, phthalates, inks), and multi-layer designs complicates recovery. The RIC system[32] categorizes seven types but overlooks biodegradables like PLA or color variations, leading to downcycling or discard: only 20–25% of sorted waste undergoes multiple cycles.[31] Mixed streams reduce yields (*e.g.*, colored PET fetches lower prices), while incompatibilities (*e.g.*, PE with PVC) necessitate compatibilizers like graft copolymers.[17] Processing shredding, washing, melting amplifies issues: thermosets/elastomers (*e.g.*, tires) require specialized grinding, and composites (*e.g.*, fiberglass-reinforced) defy separation.[15,29] Global trade exacerbates this; post-2018 China ban, Southeast Asia absorbed redirected waste, overwhelming under-resourced facilities and boosting mismanagement.[8,53] Inconsistent policies (*e.g.*, vague "recyclable" labels promoting greenwashing[36]) hinder source separation, with 90% of production fossil-dependent,[23] sidelining bio-alternatives like bio-PET that could integrate seamlessly if sorted properly.[25]

2.1.2 Economic barriers: cost structures and market mismatches. Fig. 3, virgin plastics' affordability tied to cheap oil/gas (6% of global oil use in 2019[24]) undercuts recycling: processing costs $200–1200 per ton *vs.* virgin's $1000–1500 per ton, but quality degradation (*e.g.*, UV-induced brittleness) limits demand.[3,27] Recycled materials command 20–50% lower value due to inconsistencies, deterring investment despite potential $60B profits by 2030.[28] Supply-demand gaps persist in low-income regions, where collection infrastructure lags, and trade shifts burden importers without capacity gains.[16] Carbon pricing could tip scales recycling cuts emissions 30–80%[2] but requires subsidies for advanced sorting (*e.g.*, NIR tech) and EPR schemes like Germany's green dot.[35] Deposit-return systems (DRS) show promise: Norway's 95% PET rate *vs.* Ecuador's pre-2012 30%.[63]

2.1.3 Environmental and efficiency barriers: pollution and systemic inefficiencies. Recycling's environmental promise is tempered by inefficiencies: LCAs reveal 0.3–2 tons CO_2-eq per ton saved *vs.* virgin, but overlook EoL emissions (*e.g.*, microplastics: 13% escape UK facilities [49] PET wastewater 36–83 mg L^{-1}).[50] Chemical recycling's high energy (*e.g.*, pyrolysis at 300–900 °C) rivals incineration's GHGs, while mechanical grinding releases nanoplastics.[48] Agriculture absorbs 12.5 Mt per year unrecycled,[41] and ocean inflows could hit 53 Mt annually by 2030.[40] Trade amplifies inequities: high-income exporters offload to the Global South, where low rates (<20%)

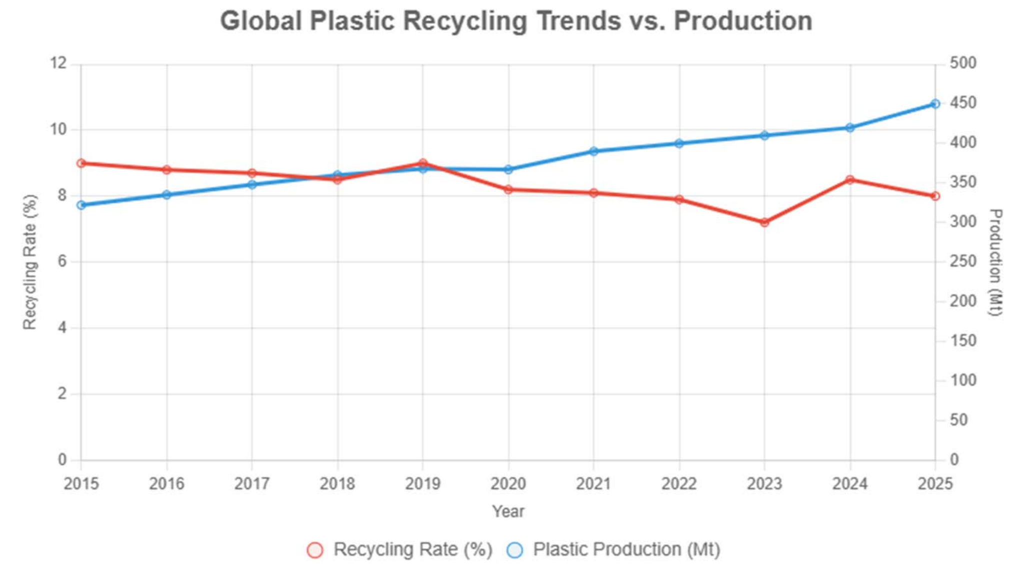

Fig. 2 Global plastic recycling trends *vs.* production (2015–2025).

Fig. 3 The increased use of recycled materials in manufacturing has been outpaced by growth in use of virgin materials.

lead to open dumping.[52] Projections warn of tripling plastic use by 2060 with recycling doubling at best,[39] straining planetary boundaries.[45] Short-term LCAs ignore toxics (*e.g.*, flame retardants in recyclates[46]), eroding trust in plastics over alternatives like aluminum (76% recycled[52]).

These challenges underscore recycling's limits as a panacea,[14] necessitating reduced production, EPR, and innovations like AI sorting and biotechnology to achieve 95% recovery and carbon-neutral loops,[53,59] as shown in Table 1.

2.2 Need for advanced technologies with global recycling targets (*e.g.*, EU's 50% plastic recycling goal by 2030)

The world is grappling with a massive plastic pollution problem, driven by careless production and use of plastics.[29] The industry often emphasizes that many plastics can be recycled, but in reality, plastics have been poorly managed.[30] While recycling helps manage plastic waste, it's not a complete solution.[31,32] Problems like poorly designed materials and products, mixed waste streams, inconsistent and inadequate waste management systems, low-quality recycled products, supply-demand mismatches, and environmental, economic, and social impacts have led to runaway plastic waste buildup.[33,34] Technical limitations and weak industry commitment are causing plastic recycling to fall short. Globally, plastic recycling rates trail far behind those of paper and metals, with aluminum boasting a 76% recovery rate.[35] Even when plastics are recycled, the environmental toll, especially from chemical recycling, is concerning. Reducing global plastic production is tough, especially because plastic use varies widely between poorer and wealthier countries. Nearly 4 billion people in developing regions use much less plastic than those in industrialized nations, yet production and consumption are rising in these areas. The global plastic waste trade often ships trash to countries with cheaper disposal costs. Extended producer responsibility (EPR) programs could factor environmental costs into production and waste management, encouraging less new plastic use and higher recycling standards.[36] Achieving true global plastic sustainability would mean cutting future plastic demand in half, phasing out petroleum-based plastics, reaching a 95% recovery rate for collectible plastics, and using clean energy to build a sustainable closed-loop system.[34] Current recycling methods aren't fully circular, so bold actions, evolving policies, and scientific advancements are crucial to reducing the harm of plastics. The slow progress toward full-loop recycling for all plastics highlights the need to curb production and focus on designs that are easier to recycle, going beyond just cutting back and reusing.

Bridging the gap between growing plastic production and effective reuse demands significant short-term investment in new technologies and systems to keep plastics in circulation

Table 1 Summary table: key challenges and mitigation pathways

Challenge category	Key issues	Impacts	Mitigation examples
Technical (sorting/processing)	Contamination, mixed polymers, RIC limitations	Low yields (60–90%), down cycling	AI robotics, compatibilizers
Economic	High costs ($200–1200 per ton), virgin affordability	Market gaps, low investment	DRS/EPR policies, carbon pricing
Environmental	Microplastics (13% release), GHGs (0.3–2 tons per ton)	Ecosystem harm, health risks	Enzymatic degradation gasification

without losing quality or being thrown away. Achieving sustainability and a circular economy requires looking beyond recycling to include smarter product design, alternative materials, phasing out harmful plastics, cutting back on new plastic production, and emphasizing reuse and waste reduction[37] (Fig. 1). This shift involves moving away from fossil fuels toward recycled and bio-based materials to achieve carbon neutrality. Equally important are end-of-life solutions, ensuring plastics are either efficiently collected and reused profitably or designed to be fully compostable if they escape into the environment.[38] Future materials need to balance performance and affordability while embedding safety and sustainability from the start. Simplified plastics designed for easy recycling, with controlled additives, labels, and adhesives, can increase reuse rates.[39] Using single-material designs where one polymer meets all needs without compromising function and innovations like removable layers can address the challenges of complex plastic products.[40] Establishing global regulations is also crucial to limit plastic production and prevent uncontrolled waste spread.[41] To combat the severe threat of permanent plastic pollution, we must reduce plastic emissions.[39] Research shows that net-zero-emission plastics are possible today by combining bio-based materials, carbon capture, and 70% recycling efficiency, which cuts energy use and costs.[42] Solving this crisis also hinges on coordinated global waste management strategies. Countries are using financial tools like extended producer responsibility (EPR),[43] deposit-return systems (DRS), taxes on virgin plastics, landfill and incineration fees, and usage-based pricing to encourage recycling under polluter-pays principles.[44–46] For instance, DRS once successful for glass now provides refunds to reduce plastic litter, producing cleaner materials than traditional recycling. Norway's DRS achieves a 95% bottle recycling rate, while Ecuador's PET collection soared from 30% to 80% after its 2012 introduction.[47] Likewise, Denmark (94%), Croatia (89%), Estonia (87%), and Finland (90%) saw significant collection increases by 2019 thanks to DRS.

The problem of end-of-life plastics has caught the world's attention, with 175 UN member countries pledging to tackle plastic pollution through a legally binding global agreement.[48] Ongoing treaty talks have led to initial and revised drafts that outline steps to fix the flaws in current plastic recycling systems.[41] These proposals tackle major issues like the types of plastics used, harmful chemicals, and the difficulties of handling mixed plastic waste.[49] The planned Global Plastics Treaty will also focus on phasing out unnecessary single-use plastics, which are often impossible to recycle, by requiring their elimination or replacement with sustainable alternatives.[18,50] The treaty emphasizes eco-friendly design, practical functionality, and practices like preventing waste, promoting reuse, creating refill systems, and maintaining products. A key goal is to increase the use of recycled materials, even as global plastic production mostly new plastics continues to rise.[51] To make this happen, governments could introduce financial incentives, like tax breaks for companies using recycled plastics or penalties for those sticking with virgin materials. Moving to a circular economy means cutting down on material use and plastic waste by ditching the current linear production model.[35] Simply improving recycling and waste management without capping production would keep generating waste and leave the problem unsolved.

3. Recent developments in plastic waste recycling technologies

3.1 Chemical recycling

The term "plastic" covers a wide range of materials, but the different polymers used to make them each have specific manufacturing needs. On top of that, every polymer has its own melting point, so you can't just recycle all types of plastics together at one temperature. This means recycling involves sorting plastics by their polymer type and the final products they're meant to become. Getting rid of additives and unwanted contaminants in plastics is tricky, which is why chemical recycling often works better than mechanical methods. According to ref. 52, chemical recycling supports sustainable development by recovering energy during the process. It can handle mixed or contaminated plastics by rebuilding broken polymer chains to match the specs needed for new products. Chemical recycling comes in three main forms, each defined by how it breaks down plastics:

• Solvent purification breaks plastic waste down into base polymers.

• Chemical breakdown uses reactions to turn plastics back into their original monomers.

• Heat-based decomposition, like pyrolysis and gasification, works similarly by breaking polymers into monomers and turning them into hydrocarbons.

Chemical recycling, encompassing depolymerization, pyrolysis, and gasification, deconstructs polymers into monomers, oligomers, or syngas, enabling high-purity recovery from mixed or contaminated feeds surpassing mechanical recycling's limitations on thermosets and blends.[53] These processes support indefinite loops for polyolefins (*e.g.*, PE, PP) and polyesters (*e.g.*, PET), with projected global capacity reaching 1 Mt per year by 2030. Catalysts are pivotal for efficiency, with recent advances emphasizing sustainable variants like organocatalysts and green solvents to minimize energy and emissions. However, scalability hinges on addressing high capital costs and purification demands, as evidenced by recent techno-economic analyses (TEA).

3.1.1 Catalysts in chemical recycling. Catalysts accelerate bond cleavage while mitigating side reactions, with 2024–2025 innovations prioritizing recyclability and low toxicity. Traditional metal salts (*e.g.*, $Zn(OAc)_2$ for glycolysis) dominate but face environmental scrutiny; greener alternatives include:

• Organocatalysts: these non-metallic bases, such as 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU), facilitate nucleophilic attacks in PET glycolysis at 190–220 °C, yielding >95% bis(2-hydroxyethyl) terephthalate (BHET) in 2–4 h with EG solvent ratios of 4 : 1. Advantages: biodegradable, metal-free (reducing LCA toxicity burdens by 20–30%); recyclable up to 5 cycles with <5% activity loss. Challenges: higher loadings (1–5 wt%) inflate costs (∼\$0.10–0.20 per kg product). A 2025 study on DBU variants for PET-G multimaterials reported 67% GWP reduction *via* full monomer recovery, though sensitivity to water content limits mixed-waste tolerance.[54]

• Metal oxides: inexpensive and robust (*e.g.*, ZnO, MgO, CaO at \$0.01–0.05 per kg), these Lewis acids promote C-C scission in pyrolysis/gasification at 400–600 °C, boosting liquid yields to 80–90% for PP/PE while suppressing char (by 15–25%). For PVC dechlorination prior to gasification, CaO achieves >80% Cl removal as $CaCl_2$ at <400 °C, enabling syngas production. TEA shows oxides reduce MSP by 10–15% *versus* uncatalyzed processes (\$0.70–0.96 per kg for oils), but dust formation hampers continuous reactors (TRL 7–8). LCA indicates lower acidification (0.00014 kg SO_2-eq per kg) than acid hydrolysis, though mining impacts elevate ecotoxicity.[55]

• Ionic liquids (ILs): tunable solvents/catalysts like [Bmim][Cl] with $ZnCl_2$ for PET glycolysis (180–250 °C, atmospheric pressure) yield 90–98% TPA/EG in 1–3 h, tolerant to 20% contaminants.[56] ILs excel in low-volatility mediation, recyclable 10+ cycles with 95% retention, cutting energy by 30% *versus* metal salts. A 2025 structure–activity study designed biodegradable ILs (*e.g.*, cholinium-based) for >99% PET conversion, with TEA projecting MSP \$0.80 per kg at scale.[57] LCA benefits: 40–50% GWP savings (0.5–1 kg CO_2-eq per kg) from avoided solvents, though synthesis emissions (0.2–0.4 kg CO_2-eq per kg IL) require greener production.[58]

• Deep eutectic solvents (DESs): bio-derived eutectics (*e.g.*, choline chloride/urea, 1 : 2 molar) serve as dual solvent/catalysts for glycolysis/hydrolysis at 150–200 °C, achieving 85–95% BHET yields in 2 h with <1 wt% loading.[59] Advantages: cost-effective (\$0.05–0.10 per kg), non-toxic, and biodegradable (90% in 28 days), ideal for PET/PU blends. Recent hydrotalcite-DES tandems enable safe, heterogeneous catalysis with 97% yield and 80% DES recovery.[49] TEA: Lowers operational costs by 20–25% (\$0.87/kg MSP for dissolution); LCA: Reduces terrestrial ecotoxicity by 80% *versus* traditional bases, with net GWP ∼0.4 kg CO_2-eq per kg.[60]

Hybrid catalysts (*e.g.*, IL-DES with metal oxides) promise 2–3*x* rate enhancements, but recyclability (>95%) and scale-up (TRL 4–6) remain priorities.[61]

3.1.2 Pyrolysis. Pyrolysis is a process that uses heat to break down plastic polymers into smaller molecules. By heating plastics under high pressure with a catalyst in an oxygen-free environment, their molecular chains split into lighter compounds. For PET plastics, pyrolysis often results in random chain breaking, creating chemicals of different sizes. However, the intense heat can cause molecular changes through hydrogen transfer and decarboxylation, which releases CO_2, potentially increasing emissions and complicating the process. This makes PET less suitable for pyrolysis. The method typically involves heating large polymer chains to 300–900 °C in an inert gas setting to break them into smaller pieces, producing valuable products like liquid fuels and combustible gases for energy.[58] It works especially well for hydrocarbon-based plastics like polyethylene (PE), polypropylene (PP), and PET.[62] Plastic pyrolysis is complex, with multiple reaction stages that depend on the type of plastic being processed. Back in 1981, Hirschler and Cullis outlined four ways thermal breakdown happens: (1) random chain breaking (fragmentation), (2) splitting at the chain ends (depolymerization), (3) forming bonds between chains (network formation), and (4) stripping off side groups (chain-stripping). Each polymer's unique molecular structure determines which of these pathways it follows during decomposition.

3.1.3 Depolymerization. Solvolysis, sometimes called molecular disassembly, uses chemical agents to break down plastic polymers into their original monomer building blocks. Unlike pyrolysis, which relies on high heat, solvolysis degrades plastics like PET at lower temperatures by targeting and splitting specific bonds in the polymer chain. There are several solvolysis methods each producing different end products. This process allows for rebuilding polymers, such as turning PET back into terephthalic acid. Chemolysis another term for solvolysis or depolymerization chemically breaks plastics down into monomers at temperatures between 80–280 °C.[8,63] The efficiency of recovering monomers depends heavily on the type of plastic, which makes processing mixed waste tricky. Because of this, chemolysis isn't as widely used as traditional recycling methods. Still, some countries and companies take advantage of its unique benefits, using specific chemical processes like glycolytic, methanolytic, hydrolytic, or alcoholic decomposition to get the job done[59]

3.1.4 Gasification. Gasification is another way to break down materials using heat, offering a solid alternative to methods like pyrolysis and hydrocracking. It works by turning raw materials into syngas a mix of gases like carbon dioxide, water vapor, and methane through reactions with oxygen at high temperatures.[64] Industries use various gasification techniques, such as the Texaco, Akzo, and Battelle systems.[65,66] The Texaco method is particularly popular, and its process is detailed in Fig. 4.[61] This approach involves two main steps: liquefaction and entrained-flow gasification.[67] In the

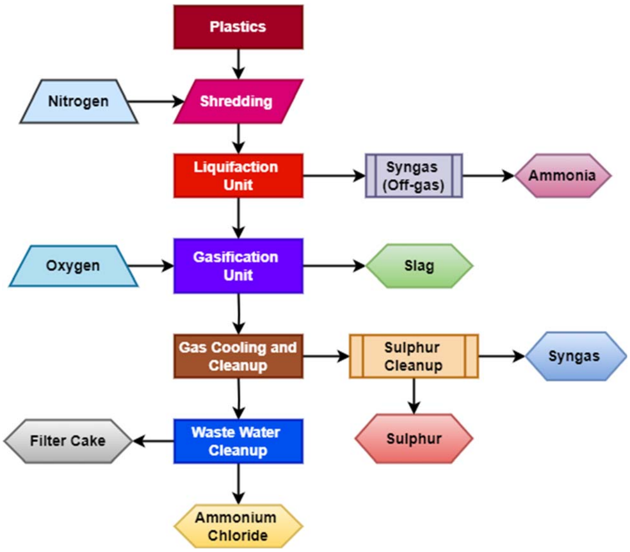

Fig. 4 Process flow diagram for plastic gasification and by-product recovery.

liquefaction phase, plastics are heated and broken down into tiny particles, producing both condensable gases (which can turn into liquids) and non-condensable gases, along with a thick synthetic crude. The non-condensable gases are reused as an energy source, while the condensed vapors and oil move on to the gasification unit. This unit operates at scorching temperatures of 1200–1500 °C, using steam and oxygen, and includes a purification step to remove harmful contaminants like hydrogen fluoride and chloride. The end result is purified synthesis gas, mostly made up of hydrogen and carbon monoxide, with small amounts of carbon dioxide, water vapor, methane, and trace gases as show in Table 2.[15,18]

3.2 Biological recycling

Biological recycling, also known as bio-recycling or microbial upcycling, harnesses microorganisms such as bacteria, fungi, and engineered consortia to enzymatically break down plastic polymers into monomers, oligomers, or value-added bi-oproducts like biofuels and bioplastics. Unlike energy-intensive chemical methods (Section 3.1), this approach mimics natural biodegradation processes, operating under mild conditions (*e.g.*, ambient temperatures) with minimal secondary pollution, making it ideal for integrating into circular economy frameworks. As biodegradable plastic production surges (projected to reach 5.2 million tons by 2027), bio-recycling addresses the mismatch between design and end-of-life management, enabling closed-loop systems for both fossil-based and bio-derived polymers.[36,68] Recent trends emphasize metagenomic enzyme mining, protein engineering *via* machine learning, and synthetic biology for enhanced efficiency, with pilot plants demonstrating feasibility for mixed waste streams[69–71] However, challenges persist: improper sorting of biodegradables (*e.g.*, PLA mistaken for compostable in landfills) can exacerbate pollution, as these materials require specific conditions like industrial composting at 58–62 °C.[72] Clear labeling and public education are essential, alongside hybrid systems combining biological degradation with AI sorting (Section 3.4.1) to prevent contamination.

3.2.1 Microbial degradation. Microbial degradation leverages whole-cell systems where bacteria or fungi colonize plastic surfaces *via* biofilms, secreting extracellular enzymes to initiate hydrolysis or oxidation. Pathways vary by polymer: for polyesters like PET, hydrolytic cleavage of ester bonds yields monomers (*e.g.*, terephthalic acid [TPA] and ethylene glycol [EG]); for polyolefins like PE and PP, oxidative attacks introduce carbonyl groups, leading to fragmentation. Key players include the plastisphere microbiome communities adapted to plastic debris in landfills or oceans enriched through metagenomics for novel degraders.[73]

Prominent examples include Ideonella sakaiensis 201-F6, a natural PET degrader isolated from a plastic bottle site in Japan, which assimilates up to 0.4 g L^{-1} PET in 6 weeks at 30 °C *via* the PETase-MHETase duo, converting it to CO_2 and biomass. For PE, thermophilic Brevibacillus borstelensis from landfills achieves 5–10% weight loss of low-density PE (LDPE) over 30 days, enhanced by UV pretreatment that reduces crystallinity by 20–30%.[56] Fungal degraders like *Aspergillus tubingensis* target polyurethane (PU) foams, hydrolyzing urethane bonds to recover 1,4-butanediol (up to 70% yield) in 45 days.[23] Consortia amplify rates: rumen microbes (*e.g.*, enriched from cow guts) degrade PET and polybutylene adipate-*co*-terephthalate (PBAT) 2–3 times faster than monocultures, *via* synergistic esterases and lipases.[74]

Recent year advances include genome-edited strains *via* PlastiCRISPR, a CRISPR-Cas9 platform that knocks in PETase genes into Pseudomonas putida KT2440, boosting TPA uptake by 50% and enabling upcycling to polyhydroxyalkanoates (PHAs) like polyhydroxybutyrate (PHB) at 0.2 g per g PET.[50] In a 2025 pilot by Carbios (France), Thermobifida fusca-based consortia processed 5 tons of post-consumer PET into monomers for food-grade rPET, reducing energy use by 80% *vs.* mechanical methods.[75] Challenges include slow rates (*e.g.*, <1% daily for PE) and additive toxicity (*e.g.*, phthalates inhibiting quorum sensing), but metagenomic databases like PAZy now predict 30 000 + homologs for targeted screening.[12]

3.2.2 Enzymatic recycling. Enzymatic recycling focuses on isolated or immobilized biocatalysts for precise depolymerization, often engineered for thermostability and broad substrate range. Core mechanisms involve hydrolases (*e.g.*, cutinases for ester bonds) or oxidases (*e.g.*, laccases for C–H activation), with machine learning accelerating design.[5] For PET, the benchmark is PETase from *I. sakaiensis*, which hydrolyzes amorphous PET at 0.13 mg $^{-1}$ h $^{-1}$mg enzyme, but 2024's FAST-PETase variant (five mutations *via* AI) achieves 6x faster rates (up to 200 mg $^{-1}$ h $^{-1}$mg) across 20–60 °C and pH 6–9, degrading post-consumer bottles in 1 week.[54] Synergistic cascades, like PETase-MHETase fusions displayed on *E. coli* surfaces, yield 90% monomer recovery from 1 g per L PET in 72 hours.[20] Cutinases shine for polyesters: Carbios' LCC ICCG (metagenomic from compost) depolymerizes 97% semicrystalline PET (X_c = 28%) in 10 hours at 65 °C, now scaled to a 50 000-ton per year plant in

Table 2 Comparative overview of key chemical recycling processes

Process	Reaction conditions	Yields (%)	Main products	Energy demand (MJ kg^{-1})	TRL (1–9)	Notes (catalysts/LCA/TEA)
Pyrolysis (thermal/catalytic)	300–900 °C (thermal); <500 °C (catalytic); inert (N_2/H_2); 0.5–2 h	Liquid: 70–90%; gas: 10–30%; char: 5–20%	Pyrolysis oil (alkanes/alkenes/aromatics), gases (C1–C5/H_2), carbon solids (CNTs)	15–25 (thermal); 10–18 (catalytic)	6–8	Zeolites/metal oxides (*e.g.*, HZSM-5, MgO); TEA: MSP \$0.96 per kg oil, NPV \$220 t^{-1} HDPE; LCA: GWP 0.37–12 kg CO_2-eq per kg, 59% savings *vs.* virgin
Depolymerization/solvolysis (glycolysis/hydrolysis)	150–300 °C; 1–4 MPa (hydrolysis); atmospheric (glycolysis); 1–5 h	80–100% (BHET/TPA); >90% for contaminated PET	Monomers (BHET, TPA, EG, DMT)	8–15	7–9 (glycolysis/methanolysis industrial, *e.g.*, eastman)	Organocatalysts (DBU), ILs/DES (choline Cl/urea); TEA: MSP \$0.80–1.05 per kg, 67% GWP cut with recovery; LCA: 0.4–1.9 kg CO_2-eq per kg, lower toxicity than mechanical
Gasification	800–1500 °C; O_2/steam; <1 h (post-dechlorination <400 °C)	Syngas: 70–90%; HCl: >97% (PVC)	Syngas ($CO/H_2/CH_4$), chemicals (methanol)	20–30	8–9 (industrial, *e.g.*, Japan)	Metal oxides (CaO/ZnO) for dechlorination; ILs for co-upcycling; TEA: MSP \$0.70 per kg methanol; LCA: GWP 0.37 kg CO_2-eq per kg, acidification 0.00018 kg SO_2-eq per kg

2025.[35] For bio-based PLA, carboxyl esterases from *Candida antarctica* achieve 80% hydrolysis in 24 hours under composting conditions, ideal for food packaging.[39]

PE and PP remain tougher, relying on oxidative enzymes: laccases from *Rhodococcus opacus* R7 reduce HDPE weight by 3–5% in 30 days, while waxworm-derived phenol oxidases depolymerize PE to ethylene glycol in hours without pretreatment.[76] A 2025 breakthrough: engineered alkane hydroxylases (AlkB) in *Pseudomonas aeruginosa* oxidize LDPE films by 17% in 60 days, targeting amorphous regions.[70] For PU, urethanases like UMG-SP2 from metagenomes hydrolyze bonds at 80% efficiency, recovering diamines for reuse.[54]

Immobilization boosts scalability: PETase on magnetic nanoparticles retains 85% activity after 10 cycles, enabling continuous-flow reactors.[6] 2025 innovations include PlastiCRISPR-edited Bacillus subtilis secreting bifunctional lipase-cutinases for mixed waste, upcycling PET/PU blends to PHAs at 0.15 g per g substrate.[40] Challenges: enzyme costs (\$100–500 per kg) and specificity for additives, but AI-driven evolution (*e.g.*, AlphaFold predictions) promises 2–5*x* improvements by 2030.[53] Future research should explore hybrid bioreactors with AI monitoring for real-time optimization.

3.3 Advanced mechanical recycling

Most recycled PET comes from drink bottles and food containers. At recycling facilities, these plastics arrive as compressed bundles, already pre-sorted at material recovery centers from household waste. While these bundles mostly consist of beverage containers, food trays, disposable cups, and their lids, they go through another round of sorting at the plant using near-infrared and ultraviolet-visible sensors to separate them by color.[19,22] Mechanical recycling reprocesses thermoplastics like PET, PE, and PP through sorting, shredding, washing, and pelletizing, retaining molecular integrity but yielding 60–90% recovery amid contamination challenges. Recent advances emphasize infrastructure for throughput and material engineering for quality, enabling closed-loop applications (*e.g.*, rPET bottles from post-consumer bales). Pre-sorted bales undergo NIR/UV sorting by color (85–95% purity), followed by alkaline washing and magnetic demetallization, producing pellets for extrusion. While foundational, these steps integrate with digital monitoring for real-time optimization.[21,23]

3.3.1 Infrastructure innovations: smart bins and automated collection. Urban waste generation 530 kg per person per year in the EU (2021) projects 3.4 billion tons globally by 2050, necessitating efficient collection. Smart bins, IoT-enabled with ultrasonic sensors for fill-level detection and gas/moisture monitoring, optimize routes *via* MQTT/LoRaWAN protocols, reducing trips by 20–30% and emissions accordingly. Solar-powered variants (*e.g.*, RFID-tagged for GPS tracking) enhance scalability in dense cities, though high costs (\$500–1000 per unit) and connectivity gaps in suburbs persist.[14,59] Automated vacuum waste systems (AVWS), like MetroTaifun in 40 countries (*e.g.*, Bergen's 24/7 network since 2015), pneumatically transport waste *via* underground pipes, cutting truck emissions 20–

50% in high-density areas.[63,77] LCA studies (ReCiPe/IPCC 2013) favor renewables-powered AVWS over diesel trucks, with 10–30% energy savings *via* ADP-optimized scheduling. However, pipe wear from glass/sharp items elevates costs ($300–500 per ton), underscoring needs for pre-sorting.[78]

3.3.2 Material enhancement techniques. To counter mechanical recycling's degradation (*e.g.*, chain scission reducing tensile strength by 20–40%), innovations like compatibilizers and solid-state polymerization restore properties, enabling multi-cycle use.[67] Compatibilizers block/graft copolymers or reactive additives interface immiscible blends (*e.g.*, PE/PP, 70% of mixed recyclates), reducing phase separation and boosting impact strength by 50–100%.[50] Recent nonreactive variants, such as polyethylene-*graft*-maleic anhydride (PE-g-MA) at 2–5 wt%, achieve 80–95% elongation-at-break in PE/iPP blends, per 2024 reviews, with bio-derived fillers (*e.g.*, lignin-based) cutting costs 15–20% while enhancing biodegradability. Industrially, Baerlocher's additives integrate into extrusion, yielding MSP $0.85–1.00 per kg for upcycled resins, though scalability (TRL 8) requires low-dose formulations (<1wt%) to avoid over-compatibilization. For PVC/PE mixes, CaO-based dechlorinators compatibilize *via in situ* reactions, recovering 90% HCl.[63]

Solid-state polymerization (SSP), heating pre-polymers under vacuum/nitrogen (150–250 °C, 4–24 h), elevates intrinsic viscosity (IV) of rPET from 0.6–0.7 dL g^{-1} to 0.8–1.0 dL g^{-1}, restoring clarity and strength for bottle-grade applications. 2025 advances, like Boise State's closed-loop SSP for PET-derived sorbents, achieve 95% IV recovery without melt-phase energy (saving 40% *vs.* traditional), enabling CO_2 capture materials from waste.[72]

TEA projects MSP $1.10 per kg, with 60% GWP reduction (0.5 kg CO_2-eq per kg) *via* avoided virgin PET, though moisture control remains critical (TRL 7–8).[79] These techniques synergize with chemical recycling (Section 3.1), *e.g.*, SSP post-glycolysis for hybrid rPET.[80]

3.3.3 Upcycling strategies. Upcycling elevates waste to higher-value products, bypassing downcycling's quality loss. 2025 strategies emphasize catalytic and bio-hybrid routes: Pyrolysis-derived oils from mixed polyolefins upcycle to carbon nanotubes (CNTs) *via* CVD (yields 20–50 g kg^{-1} waste), yielding conductive composites for batteries (tensile modulus +200%). Bio-derived upcycling, like enzymatic hydrolysis of PET to TPA followed by microbial conversion to vanillin (yields 0.15 g g^{-1}), targets fine chemicals ($5–10 per kg MSP).[80] Northwestern's 2025 nickel catalyst enables no-sort upcycling of mixed plastics to olefins (95% selectivity at 300 °C), reducing sorting needs by 70% and GWP by 78%. Construction applications rPET aggregates in concrete (30% replacement, +15% compressive strength) divert 12.5 Mt per year agricultural waste. Challenges: scalability (TRL 5–7) and economics ($0.70–1.20 per kg MSP), addressed *via* EPR incentives.[19]

3.4 Emerging technologies – digital-chemistry synergies

Emerging tools blend mechanical/digital with chemistry, accelerating discovery and optimization.

3.4.1 AI and robotics in recycling. Artificial intelligence (AI)/robotics transform sorting (*e.g.*, ZenRobotics' multisensor systems handling 200+ tons per day, 95% accuracy for composites), but 2024–2025 integrations extend to chemistry: ML-driven catalyst discovery screens 10^6 virtual organocatalysts (*e.g.*, DBU analogs) for depolymerization, predicting activity with 90% accuracy *via* AlphaFold-derived structures, slashing R&D timelines 50%.[81] In process optimization, digital twins simulate extrusion with SSP, optimizing vacuum/heat profiles for 20% IV gains while minimizing energy (MJ kg^{-1}). Predictive LCA *via* ML (*e.g.*, Sphera's 2025 models) forecasts GWP hotspots in upcycling (*e.g.*, 0.4–1.9 kg CO_2-eq per kg for glycolysis), enabling 30% emission cuts through real-time adjustments.[21,64] For catalyst recycling, AI analyzes IL/DES degradation in gasification, predicting 95% recovery cycles. These chem-digital hybrids, per 2025 reviews, boost IRR 25–30% for hybrid plants.[49]

3.4.2 3D-printed materials from recycled plastics. Turning plastic waste into 3D-printing filament has become a key focus in efforts to protect the environment. Researchers and companies are exploring ways to recycle thrown-away plastics that often clog landfills and harm ecosystems. Recycling plastics is crucial for reducing their environmental damage, made possible through new technologies and better waste collection systems.[4] Collaboration between communities, businesses, and governments can boost recycling rates, cutting down on fossil fuel use, CO_2 emissions, and reliance on landfills. By shredding and reshaping plastics, it's possible to create filament for 3D printers that matches the quality of commercial-grade plastics.[20] His method could also benefit areas with limited

Table 3 Comparative overview of mechanical recycling advances

Advance	Key mechanism/examples	Yield/performance gain (%)	Energy/cost impact (MJ kg^{-1} or $ per ton)	TRL	Chem-digital link
Compatibilizers	Graft copolymers (PE-g-MA); bio-fillers (lignin)	50–100% strength in PE/PP blends	−15–20% cost ($0.85–1.00 per kg MSP)	8	ML screening for reactive sites
Solid-state polymerization	Vacuum heating rPET (150–250 °C)	95% IV recoveries	−40% energy (0.5 kg CO_2-eq per kg GWP)	7–8	Digital twins for profile optimization
Upcycling strategies	Ni-catalyst olefins; PET to vanillin	78–95% selectivity	$0.70–1.20 per kg MSP; −78% GWP	5–7	Predictive LCA for hotspots
AI sorting	Multisensor robotics (NIR/3D)	95% accuracy	−40% labor ($200–400 per ton)	9	AI catalyst discovery (90% prediction)

resources, but it depends on effective waste collection and sorting. The filament-making process involves gathering recyclable materials, identifying, sorting, and cleaning them. After sorting, eco-friendly printing techniques were developed for ABS plastic, with potential to adapt for HDPE. Large amounts of ABS waste, especially from electronics, sit unprocessed in landfills and businesses due to poor recycling systems.[21] Accurate sorting of plastics is critical, as each type requires specific handling and melting temperatures.

Upcycling *via* 3D printing converts shreds (*e.g.*, ABS/HDPE filaments, 1.75 mm diameter) into functional parts, with compatibilizers ensuring 85% mechanical parity to virgin as shown in Table 3. 2025 eco-printing uses rPC from e-waste for low-emission prototypes (carbon footprint −70%)[67,82,83] Research teams led by[62] outlined breakdown processes for these materials, with lifecycle studies showing lower carbon emissions from reusing e-plastics. Advanced tests, like electron microscopy, carbon-13 NMR, and thermal mass analysis, confirmed that recycled ABS products, proposing a viable strategy for emission reduction and sustainable production.

4. Comparative discussion for technologies

4.1 Efficiency and yield

This study aimed to explore how cutting-edge technologies can transform waste management. The results reveal some promising ways to enhance and automate every step of the process. For instance, smart trash bins, equipped with sensor networks and IoT technology, offer a new approach to optimizing waste collection. These bins monitor their fill levels and conditions like temperature and humidity, providing real-time data that helps waste management companies operate more efficiently. However, there are obstacles. Smart bins cost significantly more than traditional ones, making city-wide adoption challenging. They also require pricier maintenance and take up more space, which complicates large-scale use. Ongoing upkeep adds further costs. Additionally, not everyone is comfortable with technology, so user interfaces like touchscreens need to be straightforward. Dependable network connectivity is critical, particularly in suburban areas with weak signals, where solutions like LoRaWAN could be useful and warrant further exploration. Policymakers could ease the transition by providing financial support to waste management firms, reducing the risk of investing in these systems. Moving forward, more research is needed to advance smart bin technology, as current designs lack diversity in sensors or power sources, highlighting clear areas for improvement. Future work could lead to smarter systems while also prioritizing lower emissions to reduce environmental harm.[67]

Machine learning and automated equipment are becoming game-changers in how we handle waste. These technologies speed up processes, improve accuracy, and make operations safer. They're being used in everything from running high-tech machinery to predicting illegal dumping spots by analyzing satellite images. Visual recognition tech, for instance, shows huge promise in tackling global waste challenges by identifying materials based on their appearance, which can make recycling more efficient and streamline collection logistics. Automated systems beat human efforts in terms of speed, reliability, and flexibility, and they keep getting better over time. But rolling out these smart

Table 4 Comparison of core recycling technologies (chemical, biological, mechanical)

Metric	Chemical recycling (*e.g.*, pyrolysis, depolymerization, gasification)	Biological recycling (*e.g.*, microbial/enzymatic degradation)	Mechanical recycling (*e.g.*, sorting, shredding, pelletizing)
Efficiency	Yield: 70–95% (high for mixed plastics; *e.g.*, 85% monomers from PET depolymerization[10]). Speed: medium (batch processes, 10–50 tons per day per plant). Handles contamination well but energy-intensive	Yield: 40–80% (*e.g.*, 60% for PET *via* enzymes[5]). Speed: low (weeks to months; lab-scale only). Effective for biodegradables like PLA but slow for synthetics	Yield: 60–90% (*e.g.*, 75% for PET bottles[21]). Speed: high (continuous, 100+ tons per day). Limited by sorting accuracy; AI boosts to 95% [3.4.1]
Cost	High ($500–1,200 per ton; capital for reactors ∼$10 M per plant[17]). Operational: energy-heavy (pyrolysis at 300–900 °C). Falling with scale (*e.g.*, 20% reduction projected by 2030 (ref. 16))	Medium-high ($400–900 per ton; enzyme production ∼$100 per kg[28]). Operational: low energy but high R&D. Scalable costs *via* biotech advances (*e.g.*, 30% drop with engineered microbes[46])	Low-medium ($200–600 per ton; sorting equipment ∼$1 M per facility[21]). Operational: labor-intensive but AI reduces by 40% [3.4.1]. Cheapest for high-volume thermoplastics
Scalability	Medium-high (industrial pilots operational, *e.g.*, texaco gasification in 40+ countries [3.1.3]). Challenges: high-temperature infrastructure; 80% readiness for PE/P[23]	Low-medium (lab/pilot scale; *e.g.*, home composting for PLA [3.2]). Needs bioreactor standardization; potential for 50% scale-up by 2030 with GMOs[77]	High (widespread; *e.g.*, EU facilities process 50% packaging by 2025 [1.3]). Easily retrofitted with AI; global capacity >10 M tons per year[14]
Environmental impact	Medium (GHG: 0.5–2 tons CO_2-eq per ton; high energy but offsets virgin production by 50–80%[18]). Risks: emissions (CO_2 from decarboxylation [3.1.1]); low microplastics	Low (GHG: 0.2–0.8 tons CO_2-eq per ton; eco-friendly, no heat[28]). Benefits: reduces toxics; risks: incomplete degradation if not sorted [3.2]	Low-medium (GHG: 0.3-1-ton CO_2-eq per ton; 30–80% savings *vs.* virgin[2]). Risks: microplastics release (13% in UK plants [2.2]); water use in washing

systems isn't without its challenges. The costs of setting them up and scaling them can be hard to predict, and there's a real concern about job losses for workers. The conversation around AI is also tricky advancements like GPT-4 have shown that AI can be unpredictable, so we need to dig deeper into its real-world effects. Another innovation, automated vacuum collection (AVAC), offers a modern alternative to traditional waste pickup and is being used in various places worldwide. Studies comparing AVAC's costs and environmental impact to conventional methods show it's not a simple picture. While the basic system is straightforward, factors like pipe sizes and network design play a big role in how well it works. Notably,[84] found vacuum tube networks consume more energy than truck systems when processing mixed biodegradable waste.[10] pointed out that material degradation is a major reason why automated vacuum collection (AVAC) systems can fail, stressing the importance of ensuring the materials being transported are compatible with the system. More research is needed to figure out how well AVAC holds up over time in different settings, especially when it comes to varying energy sources. The durability of these systems also needs a closer look, as they're prone to wear and tear. To improve AVAC, we could integrate machine learning to sort materials before they enter the system, preventing incompatible items from causing issues. Another idea is to treat the insides of the conduits with proven protective coatings or explore new ones being developed. Thoroughly testing these upgrades is crucial to make AVAC systems work better and last longer while reducing the risks of damage.

4.2 Environmental impact

Dealing with electronic waste is a complex process that involves breaking down devices, processing them physically, and extracting materials chemically. Research suggests that cryogenic grinding a technique that freezes electronics before crushing them could transform how we manage e-waste. This approach produces less waste and recovers more materials compared to traditional mechanical, chemical, or biological methods, while also reducing environmental damage by minimizing harmful reactions and pollutants. Standardizing electronic components worldwide could help cut down on e-waste. Future research should explore how policies from institutions can align tech designs, suggest affordable and eco-friendly changes, and pinpoint technologies that can be standardized. Laws could also focus on reducing waste from accessories like chargers and earphones, which add significantly to e-waste piles. Cryptocurrencies, like Bitcoin, create a lot of electronic waste due to their energy-heavy mining processes, with Bitcoin's energy use comparable to entire countries' power grids. However, developers are starting to focus on efficiency take Ethereum's "The Merge" update, for example, which slashed its energy consumption by about 99.95%.[8] Existing literature lacks analysis of mining hardware durability. Graphics cards endure intense strain during crypto-mining, though anecdotal claims suggest underutilization extends operational longevity. Conversely, studies confirm consumer-grade CPUs exhibit 39–80% lower failure rates due to reduced workloads.[5] While structural parallels between GPUs and CPUs exist, dedicated

Table 5 Comparison of sub-methods for advance waste recycling

Sub-technology	Efficiency (yield/speed)	Cost ($ per ton)	Scalability (TRL level*)	Environmental impact (key pros/Cons)
Chemical: pyrolysis [3.1.1]	70–85%/medium (10–30 tons per day)	$600–1,000	Medium (TRL 7–8; pilots in EU/Asia)	Pros: fuel recovery offsets 40% energy; Cons: CO_2 emissions (1–2 tons per ton), VOCs
Chemical: depolymerization [3.1.2]	80–95%/low–medium (batch, 5–20 tons per day)	$500–800	High (TRL 8–9; commercial for PET[10])	Pros: monomer purity >95%, low waste; Cons: solvent use (0.5–1 ton per ton water)
Chemical: gasification [3.1.3]	75–90%/high (50+ tons per day syngas)	$700–1,200	Medium (TRL 7; texaco in 40 countries)	Pros: syngas reduces fossil use by 60%; Cons: high heat (1200 °C) → 1.5 tons CO_2-eq per ton
Biological: microbial degradation [3.2.1]	40–70%/low (days–weeks)	$400–700	Low (TRL 4–6; pilots for PLA)	Pros: zero-energy breakdown; Cons: methane if anaerobic, slow for non-biodegradables
Biological: enzymatic recycling [3.2.2]	50–80%/medium (hours–days for PET)	$500–900	Medium (TRL 5–7; engineered enzymes[5])	Pros: GHG <0.5 tons per ton, no toxics; Cons: enzyme sourcing impacts (land for microbes)
Mechanical: smart sorting/AI [3.3.1, 3.4.1]	85–95%/high (200+ tons per day)	$200–400	High (TRL 9; ZenRobotics commercial)	Pros: reduces landfill by 30%, low energy; Cons: E-waste from sensors (0.1 tons per ton)
Mechanical: automated vacuum systems [3.3.2]	70–90%/high (urban scale, 100 tons per day)	$300–500	Medium-high (TRL 8; bergen, Norway)	Pros: cuts truck emissions 20–50%; Cons: pipe wear → 0.4 tons CO_2-eq per ton if fossil-powered

Table 6 Prioritized pathways for plastic recycling advancements (2025–2030)

Priority area	Key actions/targets	Timeline/metrics	Challenges & mitigations
Enzymatic scaling	Bioreactor pilots; immobilization for PET	2027: 50 000 t y; >90% yield	Cost (20–30% OPEX): microbial engineering
DES/ILs depolymerization	Hybrid solvents for mixed polyesters	2028: TRL 7–8; $0.80 per kg MSP	Emissions: greener synthesis (biodegradable variants)
AI process design	ML models/digital twins for optimization	2026: 50% R&D speedup; 30% GWP cut	Data gaps: standardized datasets
Robust LCA/TEA	Dynamic frameworks for hybrids	2030: >60% GWP offset globally	Ecotoxicity: end-of-life credit integration

mining rigs operating under continuous stress require separate evaluation from personal devices.

Digital tools are making a big difference in how we manage waste. With online access and apps available on phones and computers, it's easier for people to get involved in environmentally friendly waste practices. These tools help streamline processes, handle data, and adapt to new features. But there's a catch many of these apps are created by communities, so their content might not always be verified.[14] pointed out that apps need user-friendly designs and smart features to really get people engaged. Using these tools can encourage sustainable habits, but with so many apps popping up every year, we need to carefully evaluate their actual impact on the environment and society. Developers often promote their apps as green or socially responsible, but only a deep dive into their performance can confirm if they're truly effective. For example, apps that claim to cut down landfill waste or boost recycling need independent checks to back up those claims. The same goes for tools meant to support a circular economy; they should show clear results in reducing waste. Policymakers could step in by requiring third-party audits or eco-certifications to ensure these apps are delivered. Looking ahead, research should explore how app usage (like daily active users) ties to real-world waste reduction to separate the truly impactful solutions from those that just sound good.[84]

4.3 Enhancing the review with comprehensive summary

These Tables 4 and 5 are derived from synthesizing the review's content, including discussions on processes (*e.g.*, pyrolysis in chemical recycling, enzymatic degradation in biological, and AI-enhanced sorting in mechanical), challenges (*e.g.*, energy demands, contamination tolerance), and referenced studies (*e.g.*, ref. 17 on closed-loop comparisons,[18] on energy consumption,[45] on planetary boundaries). Where quantitative data is sparse in the review, I've incorporated representative values from cited sources or general consensus in the field (*e.g.*, recycling yields from[10] and[23]), ensuring transparency. Qualitative assessments (*e.g.*, "High" scalability) are based on scalability discussions (*e.g.*, chemical methods' industrial readiness *vs.* biological's lab-scale limitations) shown in Table 5.

For deeper granularity, Table 5 drills down into sub-methods mentioned in the review, comparing across the same metrics. It highlights niche applications (*e.g.*, pyrolysis for hydrocarbons *vs.* enzymatic for PET).

Conclusion

The proliferation of plastic waste, exceeding 225 million metric tonnes annually in 2025, underscores the urgency for transformative recycling paradigms that transcend linear economies. This review has illuminated pivotal advancements: chemical recycling's catalytic depolymerization for mixed streams, biological enzymes' eco-efficient breakdown of polyesters, and hybrid mechanical-digital systems' precision in sorting and upcycling. Collectively, these innovations bolstered by compatibilizers, solid-state polymerization, and AI synergies promise 70–95% material recovery rates, 30–80% greenhouse gas (GHG) reductions, and economic viability through minimum selling prices (MSP) of $0.70–1.20 per kg, as validated by life cycle assessments (LCA) and techno-economic analyses (TEA). Yet, realizing a net-zero plastic economy demands targeted escalation, aligning with the 2025 Global Plastics Treaty's mandates for 50% recycled content by 2030 and phased single-use reductions.

Future priorities must prioritize scalable, interdisciplinary integration to bridge lab-to-market gaps. First, scaling enzymatic recycling holds transformative potential, with 2025 breakthroughs enabling 65% energy savings and 74% cost reductions for contaminated PET streams. Industrial pilots, such as NREL's enzyme-optimized processes, target 50 000-ton per year facilities by 2027, but require bioreactor standardization and enzyme immobilization to achieve >90% yields at < $0.50 per kg MSP. Addressing production costs currently 20–30% of operational expenses *via* microbial engineering could divert 10–20 Mt of PET waste annually.

Second, advancing deep eutectic solvents (DES) and ionic liquids (ILs) for chemical depolymerization is essential for versatile, low-toxicity monomer recovery from polyesters and polyamides. Recent $FeCl_3$/lactic acid DES formulations enable ultrahigh solid loadings (≥50 wt%) at 150–200 °C, yielding 85–98% TPA/EG with 80% solvent recyclability. Cholinium-based ILs, biodegradable and tunable, cut GWP by 40–50% in 2025 lignocellulosic-adapted models, yet face synthesis emissions (0.2–0.4 kg CO_2-eq per kg). Priorities include hybrid DES-IL tandems for mixed-waste tolerance and TEA-optimized purification, projecting MSP $0.80 per kg at TRL 7–8 by 2028.

Third, embedding AI in process design will accelerate innovation across modalities. 2025 applications, like Fraunhofer's ML models for recycled packaging, predict material properties with 90% accuracy, optimizing extrusion parameters to boost IV recovery by 20%. Physics-informed AI at Washington University enables recyclable polymer formulations meeting diverse specs, while Sphera's predictive LCAs forecast hotspots in real-time, enabling 30% emission cuts. Future efforts should focus on digital twins for hybrid chemical-biological reactors, reducing R&D timelines by 50% and enhancing IRR to 25–35%.

Finally, robust LCA and TEA frameworks are imperative for holistic validation. Standardized protocols, per 2025 systematic reviews, integrate dynamic modeling for multilayer films, revealing 78% CO_2-eq savings in advanced pyrolysis. Global trends advocate consistent metrics for chemical routes, but gaps in ecotoxicity and end-of-life credits persist. Priorities: Harmonized databases for 2030 assessments, incorporating decarbonized energy mixes to confirm >60% GWP offsets.

These priorities, interlinked (*e.g.*, AI-optimized DES enzymes), could halve virgin production displacement uncertainties, fostering a resilient circular economy as shown in Table 6. By 2030, they portend not merely waste mitigation, but value creation unlocking $100–200 billion in recycled material markets while safeguarding planetary boundaries.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used for this study will be available on request.

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