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Recycled Polyolefin and Polymeric Waste for Industrial Applications: A Comprehensive Review

Aya F. Shareef*, Ali A. A. Al-Zubiedy, Nabeel H. Al-Mutairi

Department of Polymer Engineering and Petrochemical Industries, College of Materials Engineering, University of Babylon, Babylon 51001, Iraq

Corresponding Author Email: mat115.ayah.fadhiel@student.uobabylon.edu.iq

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ABSTRACT

Polyolefin-rich plastics dominate global demand, yet post-consumer waste streams often consist of mixed and multilayer recyclates, where contamination (e.g., polypropylene (PP) in polyethylene (PE), polyethylene terephthalate (PET) in polyolefins, or trace Poly(vinyl chloride) (PVC)) disrupts material properties, morphology, and long-term performance. This review presents an interphase-engineering framework that links waste-stream variability with compatibilization and technology selection. A comprehensive literature review (2000–2025) was conducted using major databases, synthesizing data on composition, processing routes, compatibilizer architecture, morphology, degradation indicators, and mechanical property retention. The review critically evaluates non-reactive and reactive compatibilization methods (including grafting during extrusion), filler-assisted interphase reinforcement, and feedstock management practices (sorting, decontamination, and purification) in case studies such as PP/PE blends, PP contamination in recycled PE, PET-polyolefin mixtures, and multilayer packaging residues. The analysis reveals that toughness recovery is primarily driven by dispersed-phase refinement and interfacial adhesion, with contaminants—especially PVC—imposing significant processing and corrosion challenges. Additionally, the review proposes metrics and reporting strategies to enhance cross-study comparability and industrial relevance. Finally, a portfolio strategy is recommended that prioritizes mechanical recycling for cleaner streams, utilizes purification/compatibilization to avoid downcycling, and reserves chemical/catalytic processes for residues unsuitable for closed-loop recycling, with testable hypotheses for scale-up.

1. INTRODUCTION

Synthetic polymers can be applied in a broad spectrum of applications in the automotive, packaging, agricultural, construction, and medical industries and in daily life [1]. The most commonly manufactured type of synthetic polymers in the world is polyolefins, which consist of over half of the total weight of polymers produced [2]. Their popularity is largely due to the fact that they are highly versatile, inexpensive, and possess attractive physical characteristics and are therefore applicable to a wide range of processing processes and final uses [3, 4]. Polyolefins are produced out of simple alkenes, including ethylene, propylene, butene, pentene, and copolymers of these alkenes, which offer wide flexibility in composition and structure [5]. They are defined by saturated hydrocarbon backbones consisting of C-C and C-H bonds primarily, which give them great chemical resistance and durability to numerous environmental factors [6, 7]. However, this very robustness, along with the high volume of production, has also played a role in the development of long-term plastic waste in the environment [1].

The most prevalent polyolefins in high volume commodity form are polyethylene (PE) and polypropylene (PP), and their efficient recycling is consequently the key to minimizing plastic pollution, resource conservation, and energy savings, as well as to a more circular economy based on plastics [8-10]. PP, in particular, combines high chemical resistance with compatibility with major processing technologies, including extrusion, injection molding, and blow molding, while also offering attractive thermal and dimensional stability at relatively low cost [11]. Commercial PP grades include homopolymers, random copolymers, typically containing about 1-8% ethylene, and impact copolymers that incorporate an ethylene-rich rubbery phase to improve toughness [12, 13]. In addition, PP tacticity, whether isotactic, syndiotactic, or atactic, strongly influences crystallinity and material properties, although most commercial PP is isotactic [14-17].

Despite extensive research on compatibilizers and recycling technologies, there is still no integrated mechanistic review that links interphase design, waste-stream contamination variability, and practical technology selection for recovering industrially relevant properties in mixed polyolefin-rich plastics. This review addresses that gap through interphase-centered benchmarking of what works, why it works, and where it fails, while also proposing testable hypotheses for scale-up.

2. REVIEW METHODOLOGY AND CONCEPTUAL FRAMEWORK

2.1 Literature search and selection

A systematic literature review was conducted in the key indexing databases (Scopus and Web of Science) and publisher databases (ScienceDirect), with the support of Google Scholar and backward/forward citation. The literature search was focused on the period 2000-2025, whereas the latest five years were considered in the discussion of the emerging advances. Titles/abstracts were screened, and then the records were evaluated in full text regarding eligibility. Peer-reviewed journal articles and authoritative reviews that reported (or critically assessed) morphology-processing-property relationships in recycled polyolefin blends and mixed-plastic recycling were eligible, whereas studies were excluded that focused on virgin polymers and did not recycle or studies that lacked enough detail on processing/processing/property relationships to be interpreted mechanistically.

2.2 Synthesis approach and central thesis

The variables that were extracted were blend composition, melt-processing route, compatibilizer/filler type and architecture, morphology descriptors (e.g. droplet size, co-continuity and interfacial features), degradation indicators (e.g. changes in melt flow rate and oxidation/chain scission signatures), and mechanical performance metrics (tensile strength/modulus, elongation at break, impact strength, and toughness). The literature is summarized under an overall thesis: to achieve predictable performance in recycled polyolefin blends, a careful design of interphase is necessary; consequently, compatibilization decisions and recycling paths are to be jointly optimized, instead of being considered as separate processes [18, 19].

2.3 Conceptual framework used in this review

The manuscript is structured according to an interphase-engineering map that connects (i) drivers of variability and incompatibility of feedstock, (ii) compatibilization methods (non-reactive, reactive, and filler-assisted), and (iii) recycling methods (mechanical, solvent-based purification, chemical/catalytic and emerging bio-based routes). This framework relates the morphology and interfacial chemistry talked about in the early part of the review to the mixed-waste case study and to technology-selection consideration in the latter part to provide a critical sense of what works, when, and why [18, 20].

3. COMPATIBILIZATION STRATEGIES

Compatibilization is one of the most effective ways to minimize the immiscibility of recycled polyolefin blends and mixed-plastic streams [21-23]. Weak interfacial adhesion and strong interfacial tension in immiscible systems favour coarse morphologies, interfacial debonding, and brittle fracture under load [24]. The compatibilizers, typically, block, graft, or reactive architectures, are inclined to the interface and either a physical adsorption on the two phases or an in-situ copolymerization in these mixtures processed in the molten state, resulting in a reduction of interfacial tension, as well as coalescence prevention and stress transfer across the interphase [25]. This interfacial mode of action is schematically depicted in Figure 1, where preferential interfacibilizer localization counteracts droplet coalescence under shear and forms molecular bridges that promote interphase load transfer [26].

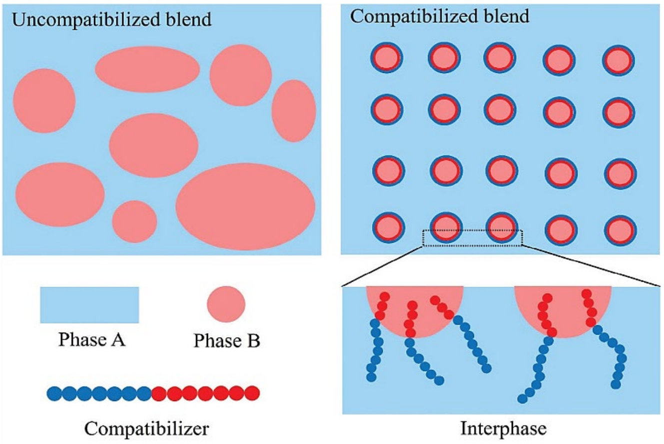

Figure 1. Schematic illustration of compatibilizer localization at an immiscible polymer–polymer interface (phases A and B)

Note: Interfacial localization reduces interfacial tension, suppresses droplet coalescence under shear, and enhances stress transfer across the interphase via physical anchoring and/or in situ copolymer formation [26].

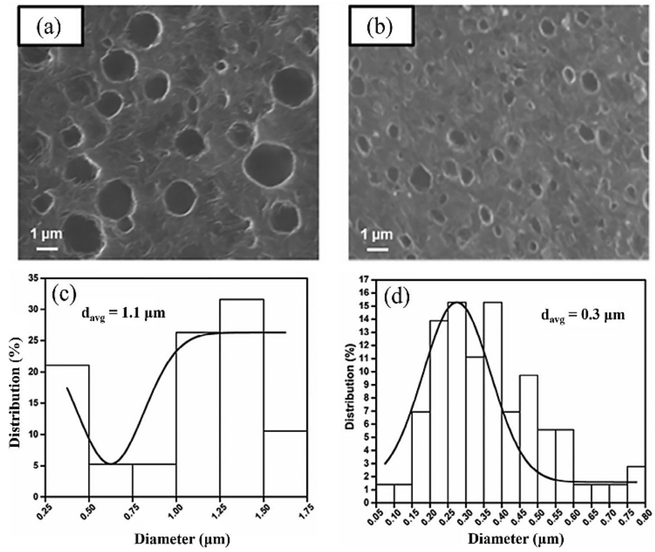

Figure 2. Scanning electron microscope (SEM) micrographs and droplet-size distributions of a PP/HDPE (20/80 wt.%) blend before and after compatibilization with 3 wt.% maleic-anhydride-grafted polyethylene (MAPE): (a) SEM micrograph of the uncompatibilized blend; (b) SEM micrograph of the compatibilized blend; (c) droplet-size distribution of the uncompatibilized blend; and (d) droplet-size distribution of the compatibilized blend

Note: The uncompatibilized melt-blended sample shows a coarse dispersed-phase morphology, whereas compatibilization refines the dispersion and reduces the average droplet diameter from ~1.1 µm to ~0.3 µm, consistent with improved interphase adhesion. Scale bars: 1 µm [27]. Polypropylene (PP); High-density polyethylene (HDPE).

In addition to improving interfacial adhesion, compatibilization also modifies the size and distribution of the dispersed phase, which strongly influences toughness and elongation at break. Figure 2 shows that compatibilizing a PP/HDPE (20/80 wt.%) blend with 3 wt.% maleic-anhydride-grafted polyethylene (MAPE) transforms the morphology from a coarse droplet structure into a finer and more homogeneous dispersion [27]. This modification is also characterized by a significant decrease in the average diameter of the dispersed phase, which decreases to 0.3 µm as compared to 1.1 µm [27]. This refinement of morphology reduces the concentration of stress on the interface, slows down the formation of cracks, and helps in the enhancement of mechanical performance [28, 29]. Practically, the recycled PP/PE and mixed-polyolefin systems in general can be compatibilized in a non-reactive, reactive, and filler-assisted way [26].

4. TYPES AND INDUSTRIAL APPLICATIONS OF PLASTIC POLYMERS

The structure-property distinction of commodity polymers is critical to recycling of mixed wastes, since polarity, crystallinity, melt viscosity and thermal stability control interfacial adhesion, phase morphology and degradation in melt processing, the same factor that leads to the blend failures in Section 5. In this regard, this section provides a brief overview of the most typical plastics found in both municipal and industrial waste streams, their main characteristics, common uses, and limitations on recycling [30, 31]. The recycling practice classifies plastics broadly as thermoplastics (re-meltable and reprocessable) and thermosets (irreversibly crosslinked and non-re-meltable), which are highly influential in determining the viable end-of-life choice [32, 33]. Low-density polyethylene (LDPE), High-density polyethylene (HDPE), PP, Polystyrene (PS), polyethylene terephthalate (PET), and Poly(vinyl chloride) (PVC) are the most widely used polymer materials in industry [34, 35].

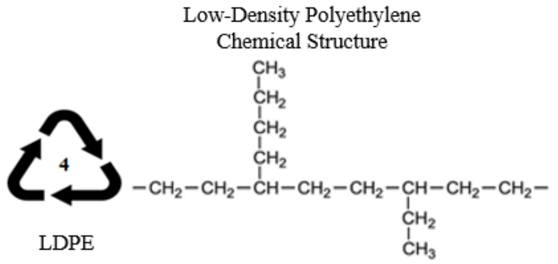

Figure 3. Repeat-unit structure of low-density polyethylene (LDPE)

Note: LDPE is a nonpolar, semicrystalline polyolefin; chain branching lowers crystallinity and density, influencing melt rheology and property retention during recycling [36].

4.1 Low-density polyethylene (Thermoplastic)

LDPE is a branched, low-crystallinity polyolefin, which results in lower density, high flexibility, and good chemical and electrical insulation; its repeat-unit structure is shown in Figure 3. These attributes make LDPE common in films, bags, liners, squeeze bottles, and protective packaging. In a recycling stream, LDPE commonly exists in both post-consumer recovered (PCR) pellets and as raw resin used for reprocessing; cleanliness and control of the thermal/oxidative history are critical to preserving ductility and processability [36].

4.2 High-density polyethylene (Thermoplastic)

HDPE has a linear backbone and significantly higher crystallinity than LDPE, which gives it greater stiffness and strength; the structure of its repeat unit is shown in Figure 4. Recycled HDPE is commonly obtained from post-consumer containers, particularly milk and detergent bottles, and is processed into products such as bottles, pipes, and FIBC regranulate. Because the physical properties of HDPE are highly dependent on grade and prior processing history, controlling contamination and melt history is essential for ensuring consistent performance in recycled products [37].

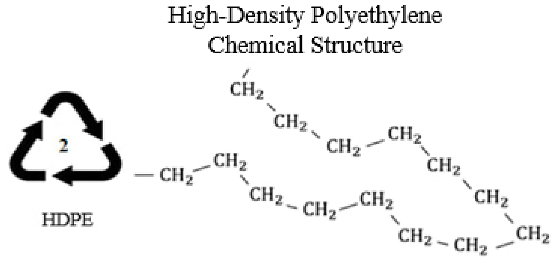

Figure 4. Repeat-unit structure of high-density polyethylene (HDPE)

Note: HDPE has a predominantly linear backbone, leading to higher crystallinity and stiffness; these features strongly affect melt viscosity, shrinkage, and recyclate performance [37].

4.3 Polypropylene (Thermoplastic)

PP is used in many applications such as packaging, textiles, automotive components, and home furnishings due to its good chemical resistance, low moisture absorption, and good electrical performance. The repeat unit of PP is shown in Figure 5. The plastic's semi-crystalline structure provides a good balance between stiffness and toughness; plus, its recyclability fits with circular manufacturing goals. In recycled applications, PP is also used as fiber reinforcement (e.g., in recycled-aggregate concrete), where formulation and processing determine mechanical outcomes [38].

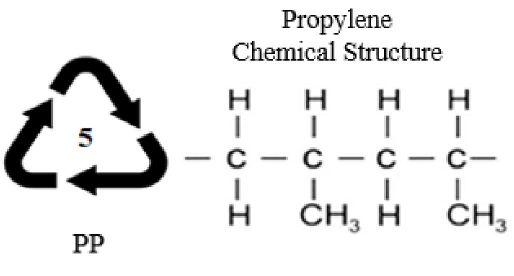

Figure 5. Repeat-unit structure of polypropylene (PP)

Note: PP is a nonpolar, semicrystalline polyolefin; tacticity and crystallinity govern stiffness, heat resistance, and sensitivity to degradation during repeated processing [38].

4.4 Polystyrene (Thermoplastic)

PS possesses a set of characteristics that support its widespread use across multiple sectors; its repeat-unit structure is shown in Figure 6. PS is used in disposable cutlery and food-service items, appliance housings, smoke-detector cases, and packaging. Expanded PS (EPS) recycling is practiced in several regions (notably in parts of Europe), but recovered PS often remains brittle, which can limit high-performance reuse. Recent work has also explored surface modification of recycled PS films for functional applications such as triboelectric energy-harvesting devices [39].

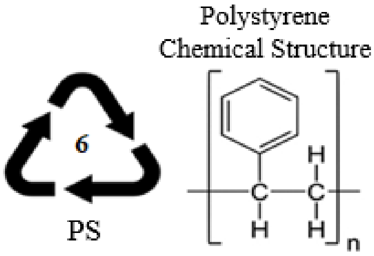

Figure 6. Repeat-unit structure of polystyrene (PS)
Note: The aromatic side group raises glass-transition temperature and stiffness, but also contributes to brittle fracture and challenges in mechanically recycled products [39].

4.5 Polyethylene terephthalate (Thermoplastic)

PET possesses a set of properties that make it suitable for a wide range of applications; its repeat-unit structure is shown in Figure 7, and it is commonly designated by the resin identification code #1. It is a dominant packaging polymer for beverage bottles and thermoformed containers and is also used in fibers, films, straps, and engineering components. In recycling, moisture control is critical because ester linkages can undergo hydrolysis at processing temperatures, contributing to molecular-weight loss and property drift if drying is insufficient [40, 41].

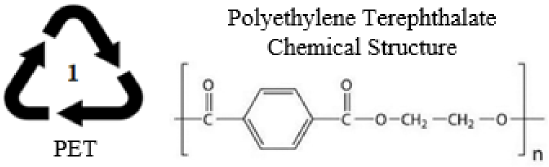

Figure 7. Repeat-unit structure of polyethylene terephthalate (PET)
Note: PET contains polar ester linkages that enable strong intermolecular interactions but also introduce hydrolysis sensitivity; moisture control is therefore critical during recycling [40].

4.6 Polyvinyl chloride (Thermoplastic)

PVC is a compound that has the properties that render it applicable in a large variety of applications as illustrated in Figure 8. Additive packages including plasticizers, stabilizers, lubricants and pigments have allowed it to be modified to its rigidity, flexibility and color and this has facilitated its wide application in construction, electrical products and consumer goods. PVC in mixed-plastic recycling is especially an issue as HCl and other acidic products emitted during the dehydrochlorination process can increase degradation reactions, corrode processing equipment, and complicate the further recycling routes. It has been demonstrated through pyrolysis based studies that PVC pollution at approximately 3 wt.% is a significant source of char generation during polyolefin waste pyrolysis [39, 42, 43]. When using PVC-specific recycling conditions, including processing plastisols, the addition of fractions of recycled PVC may result in a significant rise in viscosity. This can necessitate formulation modification, especially of plasticizer content, to ensure that there is an appropriate processing window, and acceptable properties are typically obtained within an application-specific range of recycled content [40].

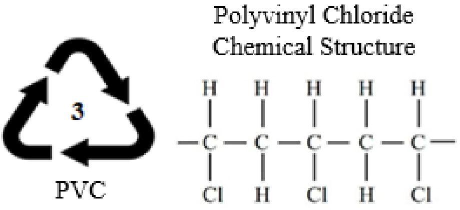

Figure 8. Repeat-unit structure of polyvinyl chloride (PVC)
Note: The chlorine-bearing backbone can dehydrochlorinate during processing, releasing HCl and driving corrosion and degradation in mixed-waste recycling [42].

PVC production across the EU-27, Norway, the UK, and Switzerland is estimated at around 6.5 million tonnes per year, which reflects its economic importance and highlights the need to improve end-of-life management, as shown in Figure 9 [41]. PVC continues to be widely used in construction, automotive, and electrical applications because of its durability, resistance to acids, bases, and salts, and relatively low cost. However, the complexity of its additive formulations and its chlorine chemistry make high-quality recycling difficult, which has prompted continued research to develop recycling chains that are both safe and effective [44].

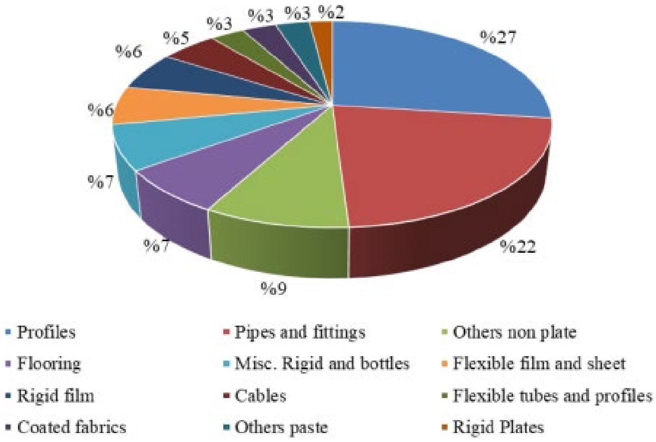

Figure 9. End-use distribution of the ~6.5 million tons of polyvinyl chloride (PVC) produced annually within the EU-27, Norway, the UK, and Switzerland [41]

Tables 1 and 2 are a summary of representative physical and mechanical properties of the main commodity plastics. Table 1 shows the morphology, density and thermal-transition temperatures, whereas Table 2 presents the degradation onset and major mechanical parameters (strength, modulus, and strain at break). Critical note on Tables 1 and 2. The values of densities, melting ranges, degradation initiating temperatures, and tensile strengths should be viewed as values, not constants, as they change depending on grade (molecular weight distribution), additives (stabilizers, plasticizers, fillers) and previous thermal/oxidative history. In the case of mixed-waste blends, contrasts that are most decision-relevant include: (i) differences in polarity and crystallinity that govern interfacial tension and phase separation (e.g., PET vs. polyolefins), (ii) mismatched melting/processing windows that facilitate selective melting and coalescence, and (iii) degradation thresholds that determine the maximum processing temperature (particularly in streams containing PVC). Where possible, future revisions of these tables should report ranges (or typical commodity-grade intervals) and explicitly indicate whether values correspond to virgin or recycled grades, as this improves the predictive link to the failure modes summarized in Section 5.

Table 1. Physical and mechanical properties of main plastic materials 1/2 [45]

Material	Morphology	Density ($g\cdot cm^{-3}$)	Glass Transition Temperature (°C)	Melting Temperature (°C)
LDPE	Semi-crystalline (40–55%)	0.91–0.93	-130 to -100 -30 to -10	110–115
HDPE	Semi-crystalline (60–80%)	0.94–0.96	-130 to -100	125–135
PP	Semi-crystalline	0.90–0.91	-20 to -21	160–165
PS	Amorphous or Semicrystalline	1.05	80–105	-
PET	Semi-crystalline	1.33–1.4	70–85	245–260
PVC	Amorphous	1.35-1.6	-50 to -80	-

Note: Low-density polyethylene; HDPE: High-density polyethylene; PP: Polypropylene; PS: Polystyrene; PET: Polyethylene terephthalate; PVC: Polyvinyl chloride.

Table 2. The primary plastic materials' mechanical and physical characteristics 2/2 [45]

Material	Initial Degradation Temp. (°C)	Tensile Strength (MPa)	Tensile Modulus (MPa)	Strain at Break (%)
LDPE	487–498	8–23	200–500	300–1000
HDPE	480–498	18–35	700–1400	100–1000
PP	450–470	21–37	1100–1300	20–800
PS	415–425	45–65	3200–3250	3–4
PET	425–445	47	3100	50–300
PVC	290–315	10–25	-	170–400

Note: LDPE: Low-density polyethylene; HDPE: High-density polyethylene; PP: Polypropylene; PS: Polystyrene; PET: Polyethylene terephthalate; PVC: Polyvinyl chloride.

5. MIXED POLYMER WASTES WITH RECYCLED POLYOLEFINS: CHALLENGES AND MITIGATION

Section roadmap. Building on the compatibilization mechanisms summarized in Section 3 and the polymer-specific processing windows summarized in Section 4, this section examines realistic mixed-waste cases where recycled polyolefins are blended with other polymers. For each case, the dominant incompatibility driver, the resulting morphology and failure mode, and the mitigation strategy (sorting, compatibilization, stabilization, or route switching) that has shown the highest robustness across studies are highlighted.

5.1 Polypropylene/polyethylene blends

PP/PE blends often exhibit weak interfacial adhesion because the two phases are inherently immiscible. This immiscibility promotes phase separation and usually lowers the mechanical performance of recycled blends. For this reason, compatibilizing agents are commonly introduced to improve phase dispersion and strengthen interfacial bonding, thereby making the recycled material more suitable for industrial use [18].

Several studies have also shown that incorporating 5–30 wt.% PP into a PE matrix can markedly reduce mechanical performance. This deterioration is generally attributed to differences in crystallization behavior, melting characteristics, and rheological properties between the two polymers [18].

Although PP/PE blends dominate polyolefin waste streams, their intrinsic immiscibility remains a major processing bottleneck, especially under industrial conditions where composition and morphology cannot be controlled precisely. Recent reviews therefore emphasize that, although mechanical recycling is still the dominant route for commodity polyolefins, feedstock heterogeneity and contamination increasingly require integrated strategies combining sorting or purification with compatibilization and, in some cases, chemical upgrading [46-49].

5.2 Polypropylene contamination in polyethylene wastes

PP contamination in PE, including both LDPE and HDPE, is a common problem in post-consumer polyolefin streams and can markedly reduce ductility even at low concentrations. As the PP content increases, the blend generally becomes stiffer and shows lower elongation at break and impact strength. Studies have shown that an ethylene-based olefin block copolymer compatibilizer can partially recover the tensile and impact properties of PP-contaminated PE blends by improving interfacial interaction and stress transfer between the phases [49]. These findings highlight the importance of contamination control and selective compatibilization for maintaining performance during mechanical recycling of PE-rich streams [19, 49].

5.3 Polyolefins/polyethylene terephthalate blends

PET is regarded as one of the worst polymers that can be mixed with polyolefins like PP because of the basic polarity and thermal and chemical structure differences. Consequently, they lead to the inherent immiscibility of PP/PET blends and extreme phase separation with poor interfacial bonding, which results in poor mechanical performance of recycled products. Recent studies have focused on reactive compatibilization to mitigate the limitations of PP/PET blends. Functionalized compatibilizers, particularly maleic-anhydride-grafted polypropylene (PP-g-MA) and epoxy-based additives such as glycidyl methacrylate, have been widely investigated. These additives promote interfacial reactions between PP and PET, which improve phase adhesion and enhance stress transfer across the interface. Consequently, noticeable improvements in elongation at break and impact strength have been reported, making recycled PP/PET blends more suitable for higher-value applications [50]. However, these approaches often require careful control of processing conditions and compatibilizer dosage, which may limit large-scale implementation and increase production costs.

Table 3. Common polymeric wastes mixed with recycled polyolefins (PO), associated recycling challenges, and mitigation strategies

Polymeric Waste Mixed with Polyolefins (PO)	**Main Recycling Challenges**	**Underlying Causes**	**Impact on Recycled Blend Properties**	**Mitigation / Improvement Strategies**	**Key References**
Polypropylene/polyethylene (PP/PE) blends	Phase separation and weak interfacial adhesion	Differences in crystallinity, density, and molecular architecture	Reduced tensile strength, impact resistance, and elongation at break	Addition of non-reactive compatibilizers (Ethylene–propylene rubber (EPR), Styrene–ethylene–butylene–styrene (SEBS), Olefin block copolymers (OBCs)); optimized processing conditions	[18, 46-49]
Polypropylene (PP) contamination in polyethylene (PE) recyclates	Increased brittleness and stiffness imbalance	Incompatibility between PP PE phases; heterogeneous morphology	Reduced elongation at break and impact strength; interfacial debonding promotes brittle fracture.	OBC compatibilizers; controlled blend ratios	[19, 49]
Polyethylene terephthalate (PET) mixed with polyolefins (PO) (PP or PE)	Severe embrittlement and poor property retention; limited tolerance to PET carryover without compatibilization or purification.	Polarity mismatch and large melting temperature difference	Loss of ductility and toughness; poor dispersion and property drift due to polarity mismatch and degradation pathways (e.g., hydrolysis for PET).	Reactive compatibilization (Maleic-anhydride-grafted polypropylene (PP-g-MA), Glycidyl methacrylate (GMA)-based chain extenders)	[50]
Polyvinyl chloride (PVC) contamination in polyolefins (PO) streams	Thermal degradation and discoloration	Hydrogen chloride (HCl) release during melt processing; presence of plasticizers	Processing instability, discoloration, and corrosion risk; severe property loss can occur even at trace PVC levels.	Advanced sorting; avoidance of mechanical blending; chemical recycling	[19, 35]
Multilayer polymer waste (PE/PP/PET/PA/EVOH) (Ethylene–vinyl alcohol (EVOH))	Poor processability and inconsistent properties	Strong interlayer adhesion; multiple incompatible polymers	Inconsistent properties and processing instability; delamination/phase separation limit high-performance applications.	Compatibilizer cocktails; filler-reinforced blends; prioritize sorting and, where needed, purification or chemical recycling routes.	[20, 51, 52]

5.4 Poly(vinyl chloride) contamination in Polyolefin (PO) streams

PVC contamination in polyolefin-rich waste streams remains a critical challenge because dehydrochlorination during thermal processing releases HCl and other chlorinated species, which can corrode processing equipment, increase operational risk, and reduce feedstock suitability for downstream recycling. Accordingly, PVC detection/removal and effective chlorine control are essential mitigation steps in the recycling of polyolefin-rich mixed-plastic streams [19, 35].

5.5 Multilayer polymer waste

Multilayer polymer waste that often comprises PE, PP, PET, and polyamides (PA) is a major problem for the traditional mechanical recycling process. The sharp variations in crystallinity, polarity, and thermal characteristics of these polymers lead to extremely heterogeneous blends that are hard to separate and reprocess. Thus, the multilayer waste can be used to obtain recycled materials that are frequently characterized by unstable and inconsistent mechanical characteristics and can hardly be utilized by industries. To solve these problems, more sophisticated compatibilization methods or other processing approaches, including reactive extrusion or chemical recycling, are becoming an increasingly popular area of investigation. These strategies are used to enhance interfacial adhesion activity between incompatible layers and to increase the performance and reliability of recycled materials that have been obtained in complex polymer waste streams [20, 51, 52]. Despite growing research interest, the recycling of multilayer polymer waste remains one of the least mature areas in polymer recycling, with limited commercially viable solutions currently available.

Interpretation of Table 3, across common mixed-waste scenarios, the dominant loss mechanism is not simply dilution of properties but morphology-driven failure: incompatible polymers form weak interfaces that act as crack-initiation sites, especially when viscosity mismatch promotes coarse dispersed domains. Compatibilization strategies are most effective when they (i) lower interfacial tension to refine droplet size, (ii) create interfacial anchors via functional grafts or block architectures, and (iii) counteract oxidative chain scission through stabilization during melt processing. From an industrial perspective, the table also illustrates a scalability rule: contamination levels that can be tolerated in closed-loop streams (e.g., controlled PP-in-PE) are often much lower in open-loop post-consumer streams, which is why combining sorting/purification with in-line compatibilization is increasingly necessary for consistent quality.

6. RECENT PROGRESS IN PLASTIC RECYCLING TECHNOLOGIES AND TRENDS

This section summarizes recent progress in polymer-recycling technologies, and the trends that shape industrial adoption are summarized in Figure 10.

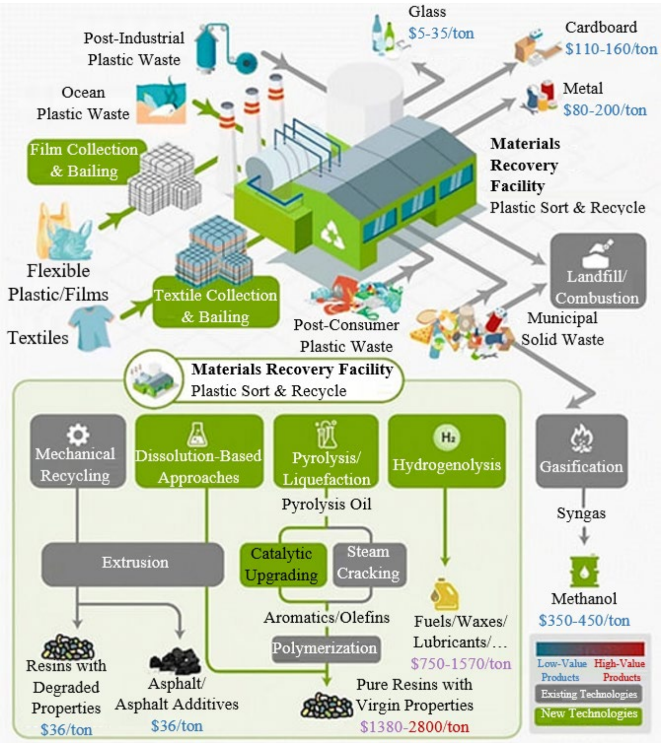

Figure 10. Schematic overview of plastic waste management routes (primary to quaternary), highlighting mechanical recycling, energy recovery, and chemical recycling pathways [53]

Mechanical recycling is the most commonly implemented due to its rather low capital intensity and established infrastructure, although repeated melt processing causes thermo-oxidative degradation, chain scission and property losses, which are further enhanced by contamination and additive variability. Such limitations have increased interest in alternative paths, such as solvent-based purification and chemical recycling (depolymerization, catalytic upgrading and thermochemical conversion such as pyrolysis) to obtain monomers or feedstocks in heterogeneous streams [53-57]. Simultaneously, catalytic process intensification (homogeneous and heterogeneous) is intended to enhance selectivity and decrease power requirements, whereas enzymatic pathways (most of them mature in PET) are able to perform depolymerization at lower temperatures under mild conditions [56, 58]. Supercritical-fluid and related separation concepts are also being explored to enhance purification and fractionation of mixed-plastic streams while limiting additional degradation.

6.1 Principal (primary) mechanical recycling: Principles and processes

Primary mechanical recycling is most effective for relatively clean and well-sorted plastic waste streams [59]. Achieving closed-loop performance with post-consumer recycled (PCR) polymers requires strict sorting, cleaning, and decontamination to reduce incompatible polymers, inks, fillers, and oxidative damage. These additional steps increase operational costs and remain among the major barriers to broader implementation [60]. Mechanical cleaning, with or without washing, is therefore necessary to minimize defects, odor, gels, and inclusions in the final products [61]. The main benefits of implementing closed-loop strategies from cradle to grave (and material circulation) are schematically highlighted in Figure 11.

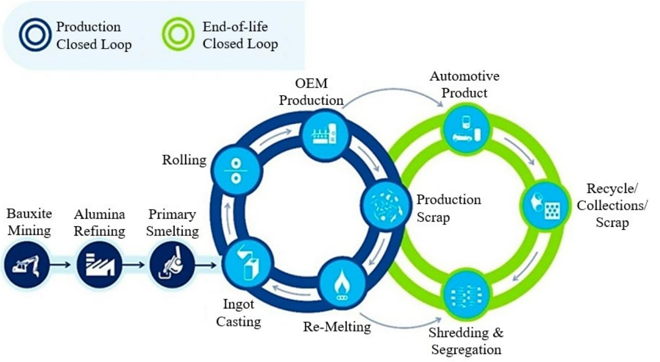

Figure 11. Schematic summary of key advantages of closed-loop and end-of-life recycling for automotive plastics (material-cost reduction, supply security, regulatory compliance, and footprint reduction) [62]

Most polymer recycling begins with a mechanical size reduction, such as shredding, crushing, or milling. This step leads to a feedstock that homogenizes with the new-product stream and is reintegrated into production cycles together with, for example, raw polymer or stabilizers, or even compatibilizers. Mechanical cleaning with or without washing is needed to minimize defects and odor, gels, and inclusions in final products [61].

After melting, recyclates can be reformed using standard thermoplastic processing methods such as injection molding, extrusion, rotational molding, and compression/heat pressing. These routes are widely applicable to PE, PP, PET, and (in controlled cases) PVC, which can be remelted and reshaped multiple times; however, each reprocessing cycle can still reduce molecular weight and alter rheology and mechanical performance [63].

To achieve high efficiency in closed-loop recycling systems, three conditions are particularly important:

- Recycled material is reintegrated into manufacturing rapidly to minimize additional aging and logistics-related contamination.
- Contaminants are removed or managed to levels compatible with the target application (including inks, paints, fillers, and incompatible polymers).
- The recyclate remains sufficiently compatible with the intended formulation (including virgin polymer and additives) to process reliably in conventional equipment [64, 65].

6.2 Secondary (open-loop) mechanical recycling: techniques and material integrity

Secondary (open-loop) mechanical recycling—so-called downcycling, as illustrated in Figure 12—transforms used thermoplastic materials into products of decreased value and/or performance compared to their original application. Unlike primary recycling, in which material quality can be maintained to some extent, secondary recycling leads to an accumulation of molecular and mechanical degradations; thus, the upcycling is often inappropriate for critical applications. Some common products are plastic composites, packaging, and construction items [66].

6.3 Chemical recycling for end-of-life plastics: Concepts and routes

In Europe, chemical recycling is increasingly regarded as a strategic complement to mechanical recycling within circular-economy and climate-policy initiatives such as the European Green Deal [67]. As shown in Figure 13, chemical recycling includes technologies that convert plastics that are difficult to recycle mechanically into monomers, feedstocks, or other chemical products. These technologies include depolymerization and catalytic routes, as well as thermochemical processes such as pyrolysis [54-56]. As a complement to mechanical recycling, these approaches can recover value from heterogeneous or contaminated streams that would otherwise be downcycled, while potentially generating higher-purity outputs for demanding applications [57]. In this review, chemical recycling refers to processes that alter the molecular structure of polymers through bond cleavage or functional transformation to produce reusable chemical building blocks [68].

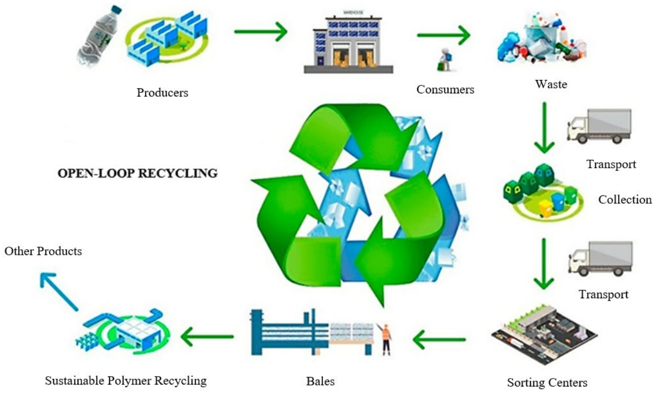

Figure 12. Principle of open-loop (secondary) recycling, where recyclates are typically downcycled into lower-performance applications due to contamination and cumulative degradation [66]

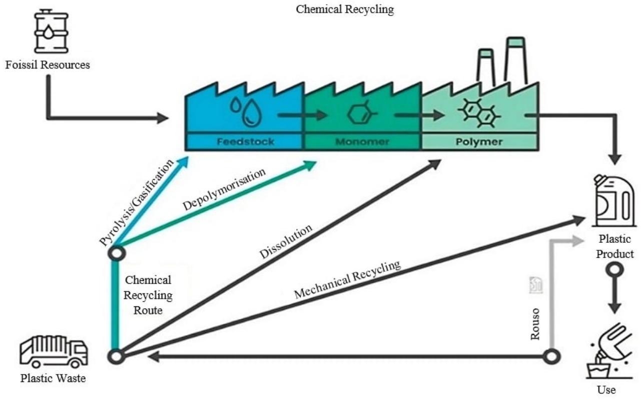

Figure 13. Simplified flow diagram of chemical recycling routes for polymers, including depolymerization, solvent-based purification, and thermochemical conversion [69]

Tables 4 and 5 provide a comparative overview of the principal plastic recycling routes, including their suitable feedstocks, key advantages, and main limitations. Mechanical recycling continues to be the dominant route for relatively clean and homogeneous waste streams. In contrast, chemical and other advanced recycling technologies are receiving increasing attention because of their potential to handle mixed, complex, and contaminated plastic wastes.

Table 4. Comparison of key plastic recycling processes, plastic wastes to be recycled, their strengths, and weaknesses

Recycling Method	Suitable Plastic Wastes	Key Benefits	Main Limitations	References
Mechanical Recycling	PET, HDPE, LDPE, PP, PS	Low energy demand; cost-effective; scalable	Quality degradation; contamination sensitivity; limited to commodity plastics	[70, 71]
Pyrolysis	Mixed plastics, PS, PE, PP	Energy recovery; handles mixed waste	Energy intensive; complex; high investment; environmental concerns	[70, 71]
Gasification	Mixed plastics, multilayer films	Produces syngas for power generation; treats mixed waste	High temperature; high cost; environmental issues; by-product handling	[55, 70]
Chemical Recycling	PET, PA, PU, epoxy, engineering plastics	Monomer recovery; closed-loop recycling; wide polymer range	High cost; hazardous chemicals; resource intensive	[55, 72]
Biological Recycling	PLA, PET, PHA	Eco-friendly; low energy; bioplastic recycling	Early-stage R&D; slow process; limited scope	[58]

Note: Polyethylene terephthalate (PET); High-density polyethylene (HDPE); Low-density polyethylene (LDPE); Polypropylene (PP); Polystyrene (PS); Poly(ethylene terephthalate) (PET); Polyethylene (PE); Polyurethane (PU); Polylactic Acid (PLA); Polyhydroxyalkanoates (PHA).

According to Table 4, it can be concluded that mechanical recycling will probably continue to be the most common path to PE and PP since the technology is relatively well-developed and, as a rule, does not consume as much energy as most other pathways. Its performance is, however limited by tolerance to contamination and accumulative degradation of the polymer.

Solvents based purification or dissolution/precipitation can sometimes be used to recover the quality of the material to near that of virgin polymers. However, these methods are constrained by solvent recovery requirements, safety and operating expenses.

More heterogeneous or contaminated plastic feedstocks can be processed by chemical and catalytic recycling. Their technical and economic feasibility; however is highly dependent on product selectivity, chlorine control in PVC containing streams, process scale and catalyst life.

In this respect, the use of technology must be considered as a portfolio decision and not a one-way decision. Mechanical recycling should take clean fractions, whereas purification or compatibilization should be used where it can avoid downcycling. Recycling of chemicals should be applied to residual streams that cannot be held in closed material loops. Techno-economic assessment and life-cycle assessment should guide such decisions [47, 48, 52].

Existing TEA/LCA data also show that the choice of routes is very sensitive to the assumptions about feed quality and process structure. Mechanical recycling is usually the least energy-demanding and greenhouse-gas-intensive of comparatively clean streams, and purification pathways heavily rely on solvent recovery efficiency and throughput. In comparison, chemical and catalytic reactions are more energy-intensive, upgrading-demanding, and catalyst-stable reactions. Comparative tests thus ought to embrace harmonized system limits and report material decision variables, including solvent recovery, energy source and contamination-related downtime, to back strong ranking of recycling options of mixed and multilayer plastic feedstocks [47, 48, 52].

6.4 Techno-economic and life-cycle considerations

In addition to the property recovery at the laboratory level, cost, throughput, regulatory compliance and supply-chain constraints are all factors that eventually dictate the adoption of industrial level. The least capital- and energy-intensive recycling path is usually mechanical recycling, although its value declines quickly in the presence of contamination which causes severe downcycling. In certain instances, purification pathways, including dissolution/precipitation, can recover the performance of materials near that of virgin polymers, but they require high solvent-recovery efficiency, process safety and reasonable operating costs. Chemical recycling has the potential to increase the scope of feedstocks to which it can be applied (especially when dealing with heterogeneous or contaminated streams), though its practicability remains highly scale-dependent, energy-price-dependent, product-upgrading-dependent, and catalyst-dependent [47, 48]. The implication of the techno-economic and life-cycle of material performance should therefore be included in future research or at least be raised in discussion. As an illustration, research must be conducted on the effect of residual moisture or chlorine-based contaminants on operating cost, downtimes and product quality [19, 52]. This reporting will be critical in coming up with solutions that are not only scientifically effective but also economically viable and scalable in circular polyolefin value chains.

Table 5. Recent developments in technologies and the research trends of each recycling process

Method	Current Research Trend	References
Mechanical recycling	• Energy- and throughput-efficient reprocessing (optimized washing, drying, and melt filtration). • Stabilization packages and multi-cycle benchmarking of property retention under realistic reprocessing histories. • Hybrid schemes combining mechanical reprocessing with compatibilization and/or targeted purification to prevent downcycling.	[18, 19, 73, 74]
Thermolysis: pyrolysis and gasification	• Catalyst development to lower temperature demand and steer product selectivity. • Process intensification (e.g., microwave/rapid heating) to improve heat transfer and control secondary reactions. • Upgrading and purification strategies to improve product quality and integration into refinery/chemical value chains.	[19, 75]
Chemical recycling	• Solvent-assisted/primary recycling and reactive-solvent routes that reduce energy demand and improve material recovery. • Closed-loop depolymerization or exchangeable-chemistry concepts to enable reuse of recovered species in new polymer production. • Improved solvent recovery and stress/property evolution control during recycling to enhance reproducibility at scale.	[54, 76-81]
Biological recycling	• Enzyme engineering (PETase/MHETase) and process optimization to accelerate depolymerization and improve robustness. • Pretreatment and separation steps that increase accessibility and reduce inhibitors in realistic waste streams. • Integration of biological steps with sorting/purification in hybrid recycling trains where applicable.	[58, 72, 81, 82]

Recent research is converging on three main directions: (i) improved mechanical recycling through more effective washing, decontamination, and energy-efficient processing; (ii) selective chemical approaches, including catalysis, controlled depolymerization, and dechlorination, to broaden the range of treatable waste; and (iii) hybrid schemes that combine physical separation with targeted chemical upgrading [19, 47]. However, many emerging methods are still evaluated using model feedstocks rather than realistic post-consumer mixtures. In addition, multi-cycle property retention is rarely assessed under industrially relevant residence times and shear histories [19, 73]. Future studies should therefore adopt standardized comparators, including virgin materials, recycled but uncompatibilized materials, and compatibilized systems where relevant. They should also report uncertainty ranges associated with feedstock variability. Taken together, these needs support the central perspective of this review: scale-up requires interphase-focused design, contamination-aware operation, and benchmarking frameworks that are directly useful for process-level decision-making.

7. CONCLUSIONS AND OUTLOOK

This review highlights that the upgrading of mixed polyolefin recyclates is essentially an interphase-engineering problem within realistic waste-stream conditions, i.e. immiscibility, viscosity incompatibility, and progressive thermo-oxidative degradation that promote coarse morphologies and weak interfaces, which ultimately lead to brittle failure. In the literature, compatibilization (non-reactive block/branched architecture or reactive grafting during extrusion) of feedstock (sorting, decontamination and, where required, purification) is the most effective means of property recovery in order to control the level of contamination and additive variability. On a technological level, more recent studies suggest the use of a portfolio approach, namely maximize mechanical recycling of relatively clean feeds, use purification/compatibilization to eliminate downcycling of moderately contaminated feeds, and use chemical/catalytic approaches on residues and multilayer mixtures that are not economically recyclable in closed-loop applications [46-48].

Key insights: (i) morphology refinement and interphase adhesion are dominant levers for toughness retention in recycled blends; (ii) compatibilizer architecture and localization (interface vs. matrix) can be as influential as compatibilizer chemistry; (iii) trace contaminants—particularly PVC—may impose processing and corrosion penalties disproportionate to their concentration [39, 42]; (iv) Reporting multi-cycle performance and realistic feed compositions is essential for industrial relevance [19, 18].

7.1 Future research directions and testable hypotheses

To accelerate translation from laboratory demonstrations to industrial practice, the following research directions are prioritized as testable hypotheses:

- Standardized multi-cycle benchmarking: Property retention (toughness/elongation/impact) should be reported over ≥ 3 recycling cycles under controlled residence time and oxygen exposure.
- Hypothesis: Strategies that stabilize interphase morphology and suppress oxidative chain scission will show significantly higher multi-cycle property retention than single-cycle benchmarks.
- Compatibilizer design rules: Systematically vary graft density and block length to quantify the trade-off between interfacial strength and melt viscosity at minimal additive loading.
- Hypothesis: An optimum in compatibilizer architecture exists where interfacial adhesion is maximized without inducing viscosity-driven processing penalties, enabling toughness recovery at low dosage.
- In-line, adaptive compatibilization: Integrate rapid composition sensing Near-infrared spectroscopy (NIR) and Fourier-transform infrared spectroscopy (FTIR) (e.g., at-line NIR/FTIR) with reactive extrusion to tune compatibilizer and stabilizer dosing in response to feed variability.
- Hypothesis: Adaptive dosing reduces batch-to-batch variability in morphology and mechanical performance relative to fixed-additive recipes.
- Contaminant management (PVC-critical): Develop practical PVC detection/removal and/or dechlorination steps to mitigate HCl-driven corrosion and catalyst deactivation in hybrid recycling trains [39, 42].
- Hypothesis: Controlling trace PVC below a process-dependent threshold will disproportionately improve equipment durability and downstream catalytic stability.
- Hybrid route optimization with harmonized metrics: Couple dissolution/precipitation purification with compatibilized mechanical recycling and benchmark against chemical recycling using harmonized TEA/LCA boundaries and assumptions [47, 52].
- Hypothesis: Hybrid trains can outperform single-route strategies when evaluated under consistent TEA/LCA frameworks, particularly for multilayer-rich or moderately contaminated feeds.

Finally, industrial scalability should be assessed alongside environmental and economic performance, ensuring that proposed strategies are not only technically feasible but also viable under realistic cost and sustainability constraints. Harmonized life cycle assessment and techno-economic analysis will be essential to bridge laboratory findings to industrial deployment and to support circular-economy targets through higher-value recycled polyolefin products.

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GENERATIVE AI STATEMENT AND CONFLICT OF INTEREST

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The authors acknowledge that artificial intelligence was used very sparingly and only for the purpose of clarifying the language of texts. It was never used in writing the scientific content, analyzing the data, or interpreting the results.

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NOMENCLATURE

EPR	Ethylene–propylene rubber
EU	European Union
EVOH	Ethylene–vinyl alcohol
FTIR	Fourier-transform infrared spectroscopy
GMA	Glycidyl methacrylate
HCl	Hydrogen chloride
HDPE	High-density polyethylene
LCA	Life-cycle assessment
LDPE	Low-density polyethylene
MAPE	Maleic-anhydride-grafted polyethylene
MHETase	Mono(2-hydroxyethyl) terephthalate hydrolase
MPa	Megapascal
NIR	Near-infrared spectroscopy
OBCs	Olefin block copolymers
PA	Polyamide
PCR	Post-consumer recycled
PE	Polyethylene
PET	Poly(ethylene terephthalate)
PIR	Post-industrial recycled
PO	Polyolefins
PP	Polypropylene
PP-g-MA	Maleic-anhydride-grafted polypropylene
PS	Polystyrene
PVC	Poly(vinyl chloride)
SEBS	Styrene–ethylene–butylene–styrene
SEM	Scanning electron microscopy
TEA	Techno-economic analysis
Tg	Glass transition temperature
Tm	Melting temperature
PETase	Polyethylene terephthalate hydrolase
PHA	Polyhydroxyalkanoates
PLA	Polylactic acid
PU	Polyurethane
wt.%	Weight percent

Greek symbols

μm	Micrometer