Review

Screw extrusion technology in waste plastic recycling

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Abstract

Screw extrusion stands as a cornerstone technology in the mechanical recycling of waste plastics, a critical endeavor in addressing the global plastic pollution crisis. This review provides a comprehensive analysis of the multifaceted role of screw extrusion in this domain. It begins by elucidating the fundamental principles of extruder design and operation, specifically comparing single-screw and twin-screw systems and their respective suitabilities for processing diverse plastic recyclates. A significant portion is dedicated to polymer-specific degradation phenomena - thermal, thermo-mechanical, and thermo-oxidative - that occur during extrusion, detailing their impact on common polymers such as polyethylene terephthalate (PET), polyolefins (polyethylene and polypropylene), polyvinyl chloride (PVC), and polystyrene (PS, HIPS). Subsequently, the review explores a wide array of quality improvement strategies essential for enhancing the

properties and value of extruded recyclates. These include pre-extrusion feedstock preparation, in-process melt filtration and devolatilization, and post-extrusion modifications through additive incorporation (antioxidants, acid scavengers, light stabilizers) and reactive extrusion (chain extension, compatibilization, filler addition). The report also critically examines the industrial challenges inherent in the screw extrusion of waste plastics, including feedstock variability and contamination, process control intricacies, economic viability concerns, and energy efficiency. Finally, an outlook on future trends is presented, covering advancements in extrusion technology, the importance of Design for Recycling, the evolving interface between mechanical and chemical recycling, and innovations in additives for upcycling. The review synthesizes current knowledge to provide an expert-level understanding, aiming to inform research, industrial practices, and policy development toward more effective and sustainable plastic recycling.

Keywords: Screw extrusion, mechanical recycling, reaction extrusion, stabilizer, waste plastic, circular economy

INTRODUCTION

Global plastic production and waste scenario

Since the 1950s, the global production and consumption of plastics - materials prized for their low cost, durability, and versatility - have undergone exponential expansion. Global annual plastic production experienced a dramatic surge, from 2 MMT in 1950 to over 450 MMT by 2018[1]. The OECD anticipates that, driven by economic/demographic growth under existing policies, global plastics usage and waste generation could both experience a near threefold increase by the year 2060[2]. This vast scale of production and consumption has given rise to acute environmental and societal problems. It is estimated that out of the approximately 9.2 billion tons of plastic manufactured cumulatively between 1950 and 2017, about 7 billion tons have already transitioned into waste[3]. According to an analysis of the global plastics sector in 2022[4], of the 400 million tons of plastic produced over the year, just under 38 million tons (9.5%) were produced from recycled plastic. Compared to the mere 9.5% that is recycled, the bulk of this waste - roughly 72% - is consigned to landfills or enters the natural environment[5], as shown in Figure 1.

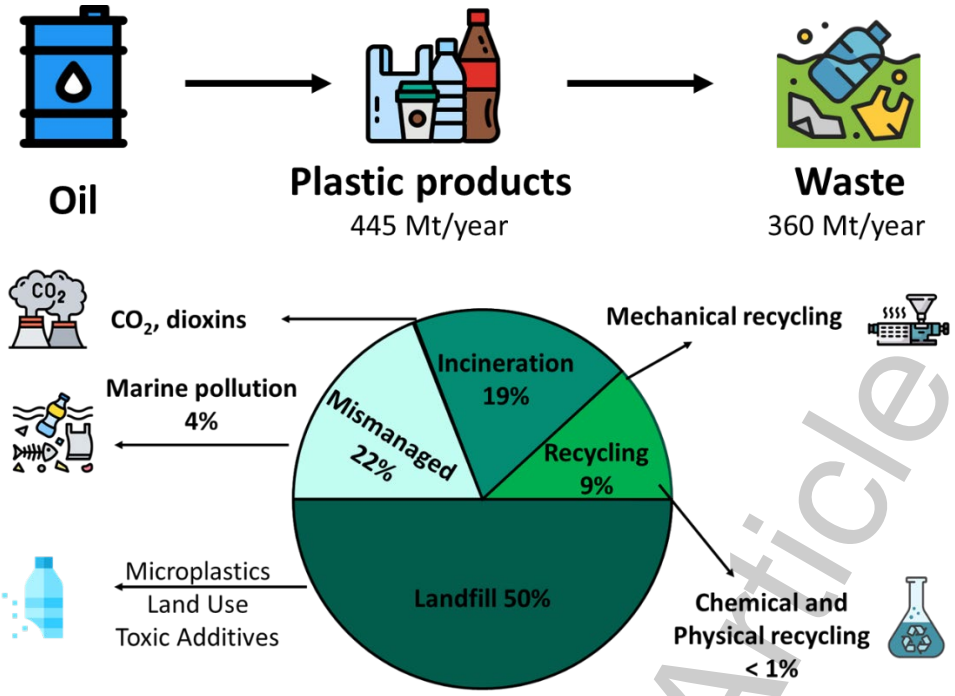

Figure 1. Global Fate of Plastic Waste: Disposal Methods and Proportions (Data based on Reference [2]).

Poor handling and disposal allow large volumes of plastic waste to infiltrate the environment through multiple routes, causing serious pollution issues[6]. Each year, an estimated 1 to 2 million tons of plastic refuse finds its way into the oceans, contributing to a situation where plastics now account for at least 85% of all marine litter[7]. Within the environment, physical, chemical, and biological actions gradually break down this waste, producing countless smaller plastic fragments. However, as these plastics break down into micrometer-sized fragments, they become small enough for ingestion by marine organisms, subsequently entering the human food chain[8]. With further degradation into nanoparticles, these nanoplastics possess the potential to penetrate the human blood-brain barrier[9].

Principal routes for waste plastic recycling

Numerous recycling methods, including both closed-loop (plastic-to-plastic) and open-loop (plastic-to-x) approaches, are becoming prevalent and fall into one of two categories: physical or chemical[10]. Physical recycling maintains the polymer's molecular structure and includes mechanical processing and solvent-based dissolution. Conversely, chemical recycling breaks

down plastic into molecular intermediates. A primary obstacle in valorizing waste plastics is their chemical inertness, which necessitates advanced approaches - such as synergistic catalysis - to effectively lower energy barriers for bond dissociation and manage the complex cleavage processes involved in upcycling[11,12]. Common methods include the depolymerization of heteroatom-containing polymers into their constituent monomers or oligomers via glycolysis, methanolysis, or hydrolysis[13-15]. Additionally, high-temperature and high-pressure techniques, such as pyrolysis and gasification, are utilized to convert plastic into fuels or chemical feedstocks[16].

Mechanical recycling, particularly methods based on melt reprocessing, holds a significant position within the current recycling infrastructure. However, conventional mechanical recycling (often using single-screw extruders) confronts numerous obstacles. Global plastic recycling rates remain disappointingly low, historically below 10%[3] and currently estimated at only around 9% globally[2]. Even within Europe, rates fall considerably short of ideal levels, although higher rates (exceeding 50%) are seen in Nordic countries[13]. Within the existing recycling infrastructure, mechanical recycling - especially techniques based on melt reprocessing - has a prominent place. However, there are many challenges with traditional mechanical recycling, which frequently uses single-screw extruders. Historically below 10% and currently estimated at only about 9% globally, global plastic recycling rates continue to be depressingly low. Although higher rates (above 50%) are observed in Nordic nations, rates even within Europe are far below optimal levels.

The loss of quality is the main obstacle to mechanical recycling. Conventional methods frequently result in reduced material qualities, which force the recycled material into lower-value goods. This “downcycling” limits the overall effectiveness of mechanical recycling in achieving true circularity for plastics hindering the ability for recycled plastics to compete with low-cost virgin materials and disqualifying them from many high-performance applications. The need for creating more sophisticated physical recycling technologies, like those that make use of twin-screw extruders, is highlighted by this performance disparity. These cutting-edge methods seek to overcome the drawbacks of downcycling by managing increasingly complicated waste streams while also, and perhaps most importantly, preserving or even improving the qualities of the recycled material.

Screw extrusion technology and its advantages

Screw extrusion stands as a fundamental and exceptionally versatile manufacturing process that has been effectively adapted for the complexities of plastic waste recycling[17]. Its primary function in this context is the transformation of often heterogeneous and contaminated plastic waste into more uniform, manageable, and processable forms, typically pellets or flakes, or in some cases, directly into new products. The technology's adaptability allows for its integration into both well-established mechanical recycling pathways and the increasingly important field of chemical recycling[18]. Plastic waste is inherently heterogeneous, comprising various polymer types, additives, and contaminants. The versatility of screw extrusion, particularly twin-screw configurations[19,20], to handle such diverse feedstocks and simultaneously perform multiple crucial operations - such as melting, intensive mixing, devolatilization of contaminants, and even facilitating chemical reactions - makes it uniquely suited to these challenges. This multi-functional capability elevates screw extruders from simple shaping tools to sophisticated processing units essential for the valorization of plastic waste.

Purpose, scope, and structure of this review

This review provides a comprehensive, expert-level analysis of screw extrusion technology, positioning it as a versatile and essential processing unit for a circular plastics economy. While screw extrusion is a cornerstone of traditional mechanical recycling, its role is rapidly expanding to serve as a critical bridge to chemical recycling pathways.

To explore this dual applicability, the review will first delve into the fundamental principles of extruder design and operation, with a particular focus on their adaptation for recycled materials. A significant portion will be dedicated to understanding the polymer-specific degradation phenomena that occur during extrusion for common plastics such as PET, polyolefins, PVC, and PS.

Furthermore, the review will explore a wide array of quality improvement strategies, including pre-extrusion feedstock preparation, in-process enhancements like melt filtration and devolatilization, and property modification through additives and reactive extrusion. Industrial

challenges - including feedstock variability, contamination, process control, economic viability, and energy efficiency - will be critically examined. Finally, by providing an outlook on future trends, this work aims to offer an integrated perspective on the extruder's function, not only as a tool for producing recycled pellets but also as a continuous reactor and pre-treatment system vital for researchers, engineers, and policymakers.

SCREW EXTRUSION: PRINCIPLES, OPERATIONAL PARAMETERS, AND COMPARATIVE ANALYSIS

Definition and key components of a screw extruder

In the context of plastic processing, a screw extruder is a complex machine meant to mix, melt, and shape polymer materials with a high degree of accuracy and homogeneity[20,21]. While the single-screw extruder (Figure 2) remains a standard for simple melting tasks, twin-screw extruders (TSEs) offer enhanced versatility through diverse screw architectures tailored to specific processing needs. These configurations are primarily differentiated by the direction of rotation and the degree of screw engagement. Plastic enters via the hopper into a temperature-controlled barrel, where a cooled feed throat prevents premature melting. A rotating screw melts and pressurizes the material, while vacuum venting removes volatile gases. The melt is filtered to remove contaminants, then forced through a die to shape the final profile, all powered by a drive system and thrust bearings.

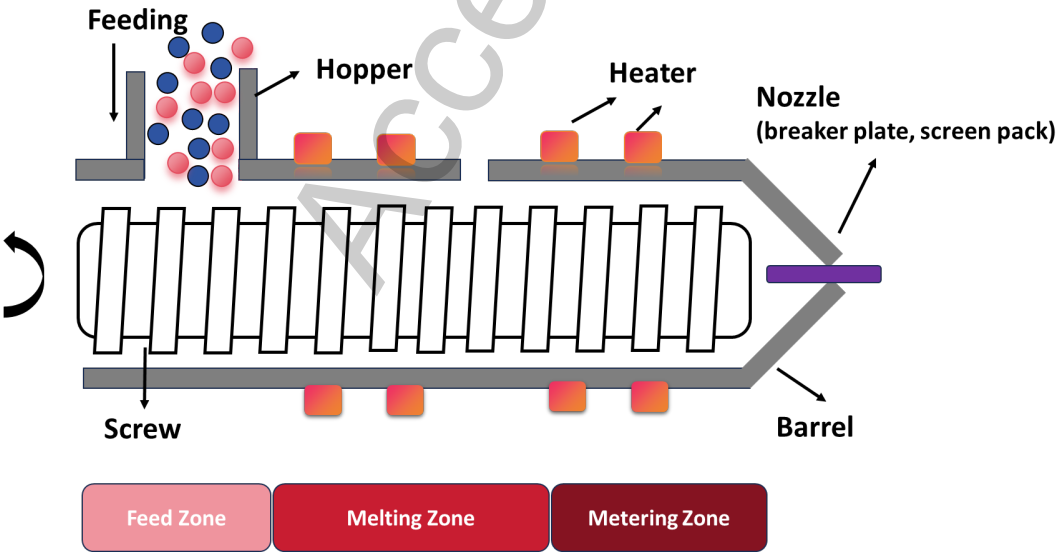

Figure 2. Schematic representation of a single screw extruder.

The operational efficacy of the extruder relies on two primary melting mechanisms: conductive heating from the barrel heaters and viscous dissipation (shear heating) generated by the screw rotation. In the context of recycling, managing the balance between these two is a critical operational procedure. For heat-sensitive recyclates (e.g., rPVC, rPET), operators must limit shear heating to prevent degradation , often by optimizing the Specific Energy Input (SEI). The extrusion process proceeds through three distinct operational steps, each governed by specific technical principles. The primary operational challenge in feed zone (solids conveying) is handling the low bulk density of recycled flakes (e.g., films, fibers). The process relies on friction between the solid material and the barrel surface to drive transport. For recyclates, "flood feeding" is often replaced by "starve feeding" using gravimetric dosers to maintain consistent output. As the screw channel depth decreases, the material is compressed in compression zone (plastication). The operational goal is to ensure the complete breakup of the "solid bed." In twin-screw systems, kneading blocks are strategically placed here to induce high shear, breaking down agglomerates and ensuring rapid melting before the material reaches the metering zone. The latter must generate sufficient pressure to overcome the resistance of the die and screen pack. Operationally, this step determines the stability of the throughput. For contaminated recyclates, this zone often integrates a melt pump to decouple pressure generation from the mixing function, ensuring a surge-free output despite feedstock variability.

Key parameters influencing the SE process

A SE processing efficiency is controlled by a number of interrelated operating and design parameters, all of which must be optimized for effective and reliable waste plastic recycling.

-Screw Speed (RPM): This parameter critically influences shear rate, mixing intensity, material residence time, viscous dissipation heating, and throughput. Typically, increasing screw speed improves output and mixing (within reasonable bounds), but it also shortens residence time and increases shear heating, which may exacerbate degradation[22].

-Feed Rate/Throughput: The degree of screw fill under starve-fed conditions is determined by the feed rate, which in turn influences the melting temperature, material residence time, Specific

Energy Input (SEI), and mixing efficiency. Although they may also increase the risk of degradation, lower feed rates (higher SEI) generally promote better mixing, reaction, and devolatilization[23].

Barrel Temperature Profile: The material's heating rate, melting speed, melt viscosity, and reaction kinetics are all impacted by the creation of discrete temperature zones along the extruder axis. When recycling heat-sensitive plastics like PVC or PET, precise temperature control is especially important[24].

Screw Configuration: This includes screw elements (conveying elements, kneading blocks, mixing elements, reverse elements, etc.) in terms of their type, geometry (e.g., pitch, width, stagger angle), arrangement sequence, and length[25]. The core of SE process design is screw configuration, which directly affects the residence time and processing intensity in different functional zones. Melting, mixing, devolatilization, pressure build-up efficiency, and degradation control are all significantly impacted. Improving product quality and recycling efficiency requires optimizing screw configuration[26].

Vacuum Level: The effectiveness of removing volatile substances is directly impacted by the level of vacuum applied in the devolatilization zone[27]. Higher vacuum levels make it easier to extract volatiles with low concentrations and low boiling points, but they also necessitate efficient vacuum systems and melt seals.

There are intricate relationships between these parameters. Changing the screw configuration affects the pressure profile, which in turn affects the fill level and devolatilization zone efficiency. For example, increasing the screw speed increases shear heat, which may necessitate adjusting the barrel temperature profile to control melt temperature. Therefore, a systematic optimization of these parameter combinations specific to the waste plastic type and recycling goal is necessary to achieve optimal processing outcomes, such as maximizing mixing efficiency, minimizing polymer degradation, and effectively removing contaminants. Design of Experiments, empirical knowledge, and increasingly complex process simulation techniques are frequently combined in this way. The interaction of these variables and the difficulty of optimizing them highlight SE technology's inherent strength and difficulty.

Comparison of single-screw *vs.* twin-screw extruders for plastic recycling

Single-screw and twin-screw extruders present distinct advantages and disadvantages for plastic recycling, as shown in Table 1. Single-screw extruders are characterized by their lower cost, simpler operation, and ease of maintenance, making them suitable for processing common thermoplastics with limited contamination. However, they offer lower mixing capability and throughput compared to their twin-screw counterparts. Twin-screw extruders, while having higher initial and maintenance costs and requiring more complex operation, provide superior mixing, higher throughput, and greater material versatility, including the ability to handle contaminated and high-viscosity materials. They are also often more energy-efficient in high-output scenarios and less sensitive to foreign bodies due to better degassing and filtration capabilities.

Table 1. Comparison of single-screw *vs.* twin-screw extruders for plastic recycling

Feature	Single-Screw Extruder	Twin-Screw Extruder
Mixing capability	Limited, less effective for complex formulations or high filler content.	Superior, excellent for uniform dispersion of additives, fillers, and colorants; crucial for mixed plastics and compounding.
Throughput	Generally lower for the same screw diameter.	Generally higher, dual-screw design allows for larger surface area for melting and conveying.
Cost	Lower initial purchase and maintenance costs.	Higher initial purchase and maintenance costs due to complex design.
Operational complexity	Simpler to operate and maintain, requires less technical skill.	More complex operation and maintenance, requires higher technical skills and potentially more training.
Material versatility	Suitable for a range of common thermoplastics, but less effective with high-viscosity or complex materials.	Can handle a wider variety of materials, including high-viscosity, high-fill, and heat-sensitive materials; more adaptable to diverse polymer properties.

Suitability for contaminated materials	More sensitive to metallic foreign bodies and may struggle with high contamination.	Less sensitive to metallic foreign bodies; often equipped with better degassing and filtration capabilities for handling contaminated waste streams.
Energy efficiency	Can be lower in high-output applications compared to co-rotating twin-screw.	Co-rotating designs can be more energy-efficient in high-output scenarios; potential for energy savings by processing undried materials in some cases.
Typical application	Ideal for processing a single type of thermoplastic and for applications where high levels of mixing are not required.	complex tasks like compounding, mixing, and specialized applications in food and pharmaceuticals due to their superior control and mixing capabilities

KEY CHALLENGES IN EXTRUSION-BASED RECYCLING

Polymer degradation during Melt processing

General degradation mechanisms

The primary challenges during the melting process are from the degradation of material properties during reprocessing, where changes in polymer chain length lead to reduced mechanical performance, as shown in Figure 3. The primary mechanisms involved are thermal, thermo-mechanical, and thermo-oxidative degradation. Thermal degradation occurs due to the material's prolonged exposure to the high temperatures necessary for melting[28]. The heat-induced damage is often compounded by thermo-mechanical degradation, where the intense shear forces from the rotating screw physically break apart the polymer chains[29]. Furthermore, the presence of air or dissolved oxygen in the polymer at these elevated temperatures can lead to thermo-oxidative degradation[30], a chemical process that further compromises the material's molecular structure through oxidative reactions. These mechanisms are not mutually exclusive and often act synergistically. For example, shear forces can generate free radicals on polymer chains through a thermo-mechanical effect. These radicals subsequently react with available oxygen, leading to thermo-oxidative degradation, a process significantly accelerated at elevated melt temperatures. This interplay is particularly critical for recycled plastics, as they often enter the extrusion process

with a history of prior degradation and potentially depleted levels of their original stabilizing additives, making them more susceptible to further deterioration.

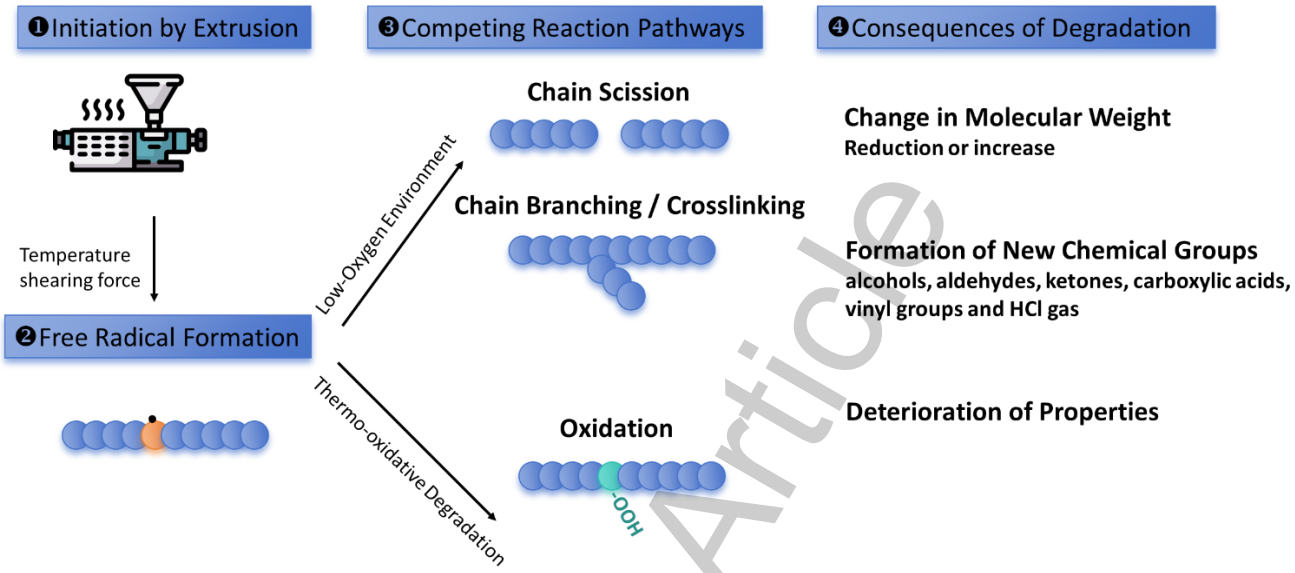

Figure 3. General reaction scheme of polymer undergoing extrusion.

The consequences of these degradation processes include chain scission (a reduction in polymer molecular weight), crosslinking (an increase in molecular weight, potentially leading to gel formation), changes in the molecular weight distribution (MWD), and the formation of new chemical groups (e.g., carbonyls, vinyls) or volatile organic compounds (VOCs)[31]. The specific degradation pathway and its severity depend heavily on the polymer type and precise processing conditions, such as shear rate, residence time, and oxygen availability. Furthermore, the quality of the incoming feedstock - specifically the nature of contaminants and prior thermal history - plays a decisive role. Contaminants present in recycled plastics, such as food residues, paper, metals, or even incompatible polymer types, can act as catalysts or initiation sites for these degradation reactions[32]. This can accelerate the deterioration of the polymer's properties to a greater extent than would be observed for virgin material processed under identical extrusion conditions.

Comparative degradation behaviors and mitigation strategies

Distinct polymer architectures dictate unique degradation pathways during extrusion, presenting specific challenges for recyclers that require tailored mitigation strategies. Summary of Degradation Behaviors for Common Polymers During Extrusion was shown in Table 2.

Table 2. Summary of degradation behaviors for common polymers during extrusion

Polymer	Typical Processing Temp. Range (°C)	Primary Degradation Mechanism(s)	Key Degradation Products & Effects
PET	260 - 280	• Hydrolysis due to residual moisture . • Thermal and thermo-oxidative degradation .• Catalytic degradation from PVC impurities (HCl).	• Significant reduction in intrinsic viscosity and melt strength .• Loss of mechanical properties.
PE	180 - 280	• Competing reactions of chain scission and crosslinking via thermo-oxidative pathways.	• Unpredictable changes in Melt Flow Index (MFI) and viscosity . • Potential for gel formation from crosslinking . • Reduced elongation and impact strength.
PP	200 - 280	• Predominantly chain scission via a β-scission mechanism.	• Consistent and marked increase in MFI and drop in viscosity .• Severe loss of ductility and impact strength, leading to brittleness.
PVC	180 - 210	• Extreme thermal instability leading to autocatalytic dehydrochlorination.	• Release of corrosive hydrogen chloride (HCl) gas . • Severe discoloration (yellow to black) and embrittlement.

HIPS	200 - 260	• Thermo-oxidative degradation of the polybutadiene (PB) rubber phase, which provides toughness.	• Severe loss of impact strength as the rubber phase is compromised

Polyolefins (PE and PP): Polyethylene (PE) and Polypropylene (PP) exhibit fundamentally opposing behaviors under identical processing conditions. PP predominantly undergoes chain scission via a β-scission mechanism[33], leading to a consistent and marked inscrease in Melt Flow Index (MFI) and a loss of ductility[34]. Conversely, PE - depending on its branching and oxygen availability - is prone to competing reactions where crosslinking can dominate, resulting in increased viscosity and the formation of gels[35-37]. This divergence creates a severe processing challenge for mixed polyolefin streams: as the blend is extruded, the PP phase becomes less viscous while the PE phase may harden, leading to a heterogeneous melt with unstable flow properties. To mitigate this, recyclers must employ synergistic antioxidant blends to arrest radical formation and often incorporate compatibilizers that can bridge the rheological gap between the degrading phases[38].

Condensation Polymers (PET): In contrast to the radical-driven degradation of polyolefins, Polyethylene Terephthalate (PET) is defined by its sensitivity to moisture[39]. The presence of ester linkages makes PET susceptible to hydrolysis if processed without rigorous drying; even trace moisture levels can trigger rapid chain scission, causing a significant reduction in intrinsic viscosity (IV) and melt strength. This renders the material unsuitable for blow molding applications. Consequently, the primary solution involves strictly controlling moisture (< 50 ppm) or employing reactive extrusion. Strategies using chain extenders, such as epoxy-functionalized additives, are standard practice to “repair” the polymer chains and restore the IV to virgin-like levels (approx. 0.80 dL/g)[40].

Thermally Unstable and Multiphase Systems (PVC and HIPS) Certain polymers present unique instability challenges that require specific stabilization packages. Polyvinyl Chloride (PVC) is chemically unstable and prone to autocatalytic dehydrochlorination, releasing corrosive hydrogen chloride (HCl) gas that accelerates further degradation and damages equipment[41]. Successful processing is therefore entirely dependent on the continuous presence of acid

scavengers (e.g., calcium/zinc soaps) to neutralize HCl immediately upon generation. Similarly, High-Impact Polystyrene (HIPS) faces a targeted threat: its polybutadiene rubber phase - which provides toughness - oxidizes preferentially compared to the styrene matrix[42]. This selective degradation leads to embrittlement, necessitating the use of antioxidants specifically targeted at protecting the diene rubber phase to retain impact resistance

Feedstock contamination and impurities

Contaminants can include non-plastic materials (paper, metal, glass, food residues, dirt), other incompatible plastic types, inks, adhesives, and additives from previous applications[43]. These impurities can degrade the properties of the recycled plastic, cause processing issues in the extruder (e.g., screen clogging, wear), and affect the appearance and performance of the final product. The presence and behavior of various additives - such as antioxidants, chain extenders, fillers, and plasticizers - initially designed for the polymer's first life cycle, can further complicate recycling by contributing to variability in recyclate quality and not being effective over repeated processing cycles. For example, Eriksen *et al.*[44] conducted a study of provide consistent quantitative data on the presence of selected metals in plastic samples of different origins and polymer types. As shown in Figure 4, washing did not consistently reduce concentrations across all metals, the results suggest that surface contamination is not the primary source of these elements.

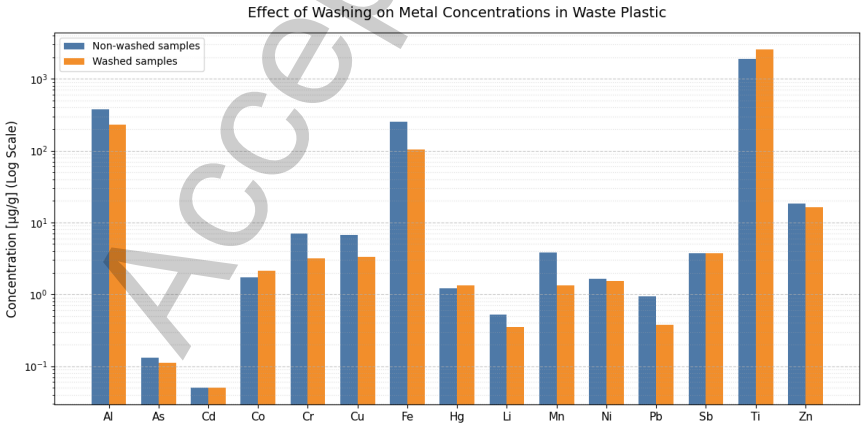

Figure 4. Comparative analysis of metal concentrations in non-washed versus washed waste plastic samples, presented on a logarithmic scale. (Data was obtained from Ref. [44]).

To effectively recycle plastics, a multi-stage purification process is essential. Upstream sorting and cleaning form the initial phase, involving manual, mechanical, or advanced optical[45]/AI-

driven systems[46] to segregate plastic types and eliminate large contaminants, followed by intensive washing and drying. Next, in-extruder melt filtration[47] utilizes screen packs to physically remove solid particles from the molten plastic; advanced systems like continuous screen changers or integrated units can manage higher contamination levels without halting production[48]. Finally, devolatilization or degassing occurs within the extruder, where venting systems, often under vacuum, extract volatile impurities such as moisture, residual monomers, solvents, or low molecular weight degradation products.

Processing of complex and immiscible mixtures

A further impediment to recycling mixed plastic waste lies in the discrepancies in melting points and requisite processing temperatures of the constituent polymers, as demonstrated in Figure 5. Moreover, mechanically recycling mixed plastic waste streams containing incompatible polymers is particularly challenging, as direct blending often results in materials with poor interfacial adhesion and inferior mechanical properties. The most preferred approach is intensive sorting, which aims to enhance sorting efficiency to generate purer single-polymer streams, thereby simplifying subsequent processing. Alternatively, when dealing with unavoidable mixed plastics, compatibilization can be employed[49]; this involves incorporating additives, known as compatibilizers, during the extrusion process to improve adhesion between immiscible polymer phases and consequently enhance the properties of the mixed plastic recyclates[50], a task for which twin-screw extruders are particularly well-suited due to their excellent mixing capabilities.

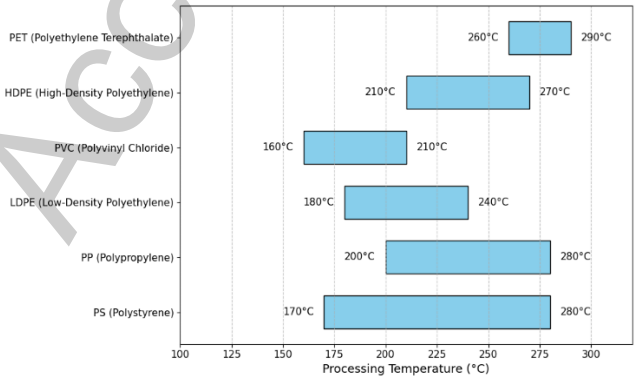

Figure 5. Processing ranges for the six most common packaging polymers.

Limitations and economic considerations

Scaling up screw extruders from pilot to industrial operations presents a multifaceted challenge (Figure 6), moving beyond simple geometric increases to navigate complex interplay between the length-to-diameter (L/D) ratio, screw geometry, and throughput rates. Successful scaling requires a deep understanding of how these factors interact to maintain product quality and process stability.

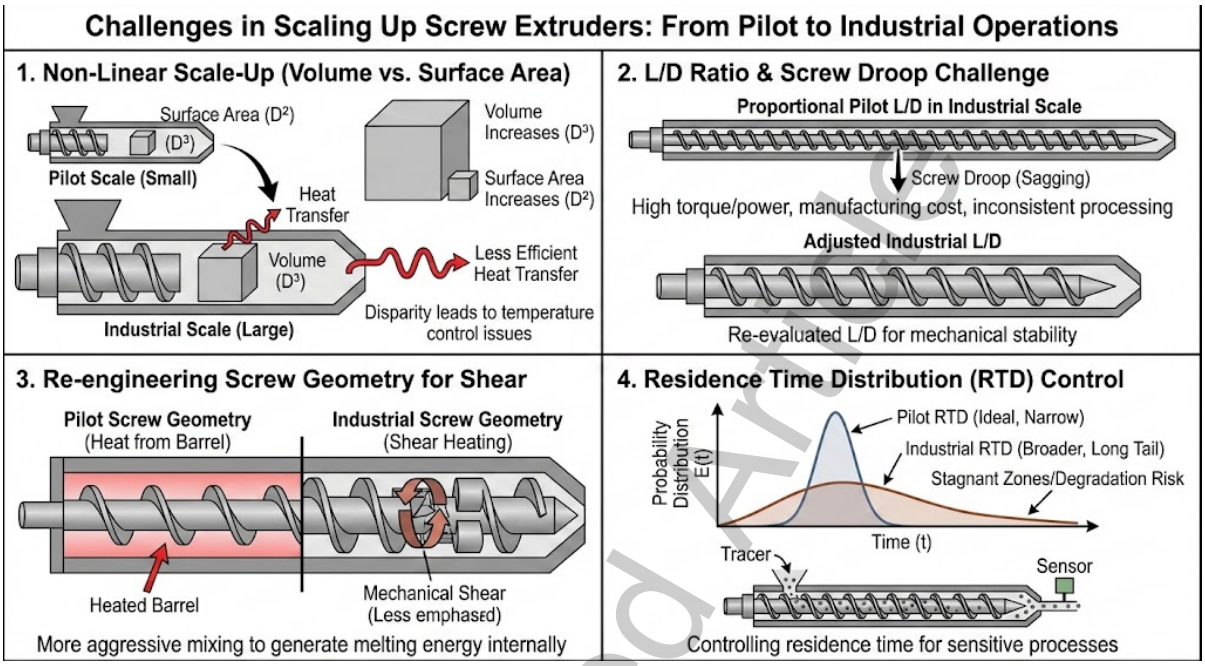

Figure 6. The challenges in scaling up screw extruders.

The Non-Linear Nature of Scale-Up. A fundamental challenge in scaling up screw extruders is that the process is not linear. Simply building a larger version of a pilot-plant extruder with geometrically similar parts will not yield the same results. The volume of the extruder increases by the cube of the scale-up factor, while the surface area of the barrel, which is crucial for heat transfer, only increases by the square. This disparity means that the larger machine will have a significantly different heat transfer characteristic, often leading to difficulties in controlling the melt temperature.

The Length-to-Diameter (L/D) ratio, a critical parameter that governs residence time, mixing, and melting in a screw extruder, cannot be simply replicated when scaling from pilot to industrial operations. While a moderate L/D ratio is often sufficient and adaptable in a smaller pilot setting, maintaining the same ratio in a larger machine creates significant engineering challenges. A proportionally longer screw in an industrial-scale extruder demands substantially higher torque

and power, increases manufacturing complexity and cost, and is susceptible to "screw droop" - sagging under its own weight, which causes inconsistent processing and wear. For these reasons, engineers must carefully re-evaluate and adjust the L/D ratio, along with the screw's overall geometry, to suit the new thermal and mechanical dynamics of the larger, industrial-scale equipment.

The screw geometry, encompassing the design of its feed, compression, and metering zones, is central to the extrusion process and must be fundamentally re-engineered when scaling from a pilot to an industrial operation. While pilot screws can be easily modified to test various configurations, an industrial screw must be adapted for higher throughput and different heat transfer dynamics. This requires optimizing the flight depth and helix angle for increased volume and, more importantly, redesigning the mixing and kneading elements. Due to the larger volume-to-surface area ratio in industrial extruders, more melting energy must be generated from mechanical shear provided by the screw itself, rather than from the heated barrel. This necessitates a more aggressive or strategically placed mixing section to ensure uniform melt and dispersion without degrading the material, and also requires appropriately scaled degassing sections. Therefore, the primary goal is to replicate the material's thermomechanical experience, which paradoxically requires a screw configuration that is often significantly different from what was optimal at the pilot scale.

The Residence Time Distribution (RTD) serves as a temporal fingerprint for the screw extrusion process, defining the time fluid elements spend traveling from inlet to outlet. This probability distribution provides critical insights into flow behavior and mixing efficiency, with its shape revealing the mean residence time, the spread (variance), and the presence of any problematic long "tails" indicating stagnant zones where material can degrade. Controlling the RTD is especially crucial for sensitive processes like reactive extrusion, where a narrow distribution centered around the optimal reaction time is essential for maximizing yield and preventing unwanted side reactions. The RTD is dynamically influenced by operating conditions, primarily feed rate and screw speed, and by geometric factors such as the L/D ratio and the specific design of screw elements. It is measured experimentally by introducing tracers (like colored pigments or fluorescent dyes) and monitoring their concentration at the outlet over time, with advanced techniques allowing for local RTD measurement within specific screw sections. To predict and understand this complex

behavior, engineers often use conceptual models from chemical reactor theory, representing the extruder as a network of ideal reactors.

QUALITY IMPROVEMENT STRATEGIES FOR EXTRUDED RECYCLATES

Addressing the degradation, contamination, and miscibility challenges outlined in Section 3 requires a multi-faceted approach involving process optimization, advanced material formulations, and reactive modification. The following sections detail these key strategies for enhancing the quality and value of extruded recyclates. The inherent degradation and contamination associated with recycled plastics necessitate various strategies to improve the quality of the extruded material. These strategies can be applied before, during, or after the extrusion process.

Process optimization

Pre-extrusion preparation

Effective pre-extrusion preparation is a foundational and critical phase in plastic recycling that directly dictates the quality of the final product and the efficiency of the entire operation. This multi-step process begins with sorting, Combination of optical spectroscopy and machine learning to sort plastic waste (Figure 7) was recently draw a lot of attentions[51]. This process often use technologies like NIR spectroscopy[52], to separate plastics by polymer type and remove non-plastic contaminants. Following sorting, a thorough cleaning and washing stage eliminates surface residues like dirt, food, and adhesives, which is paramount for high-purity applications. The cleaned material is then ground or shredded into uniform flakes or pieces to ensure consistent feeding and melting within the extruder. For hygroscopic polymers such as PET, a crucial final drying step is required to remove absorbed moisture[53] and prevent severe hydrolytic degradation during melt processing. The thoroughness of these preparatory stages significantly reduces the operational burden of downstream processes like melt filtration and devolatilization, prevents irreversible damage to the polymer, and is the most vital investment for producing a high-quality, consistent recyclate.

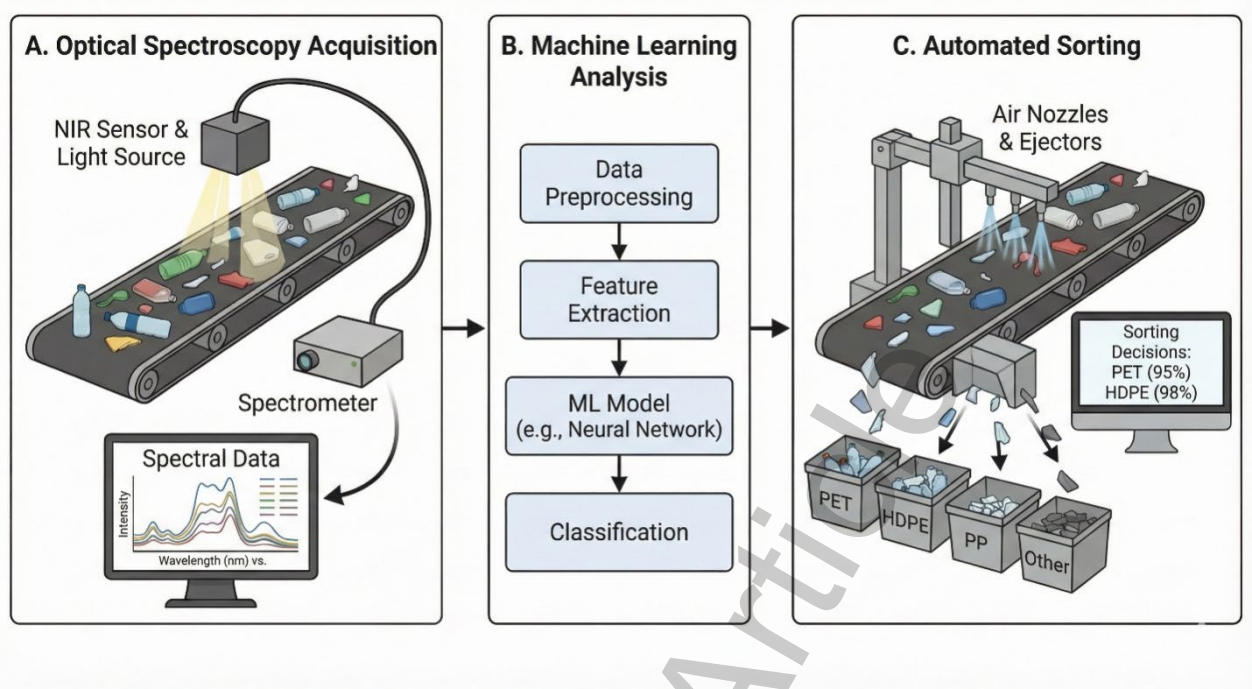

Figure 7. Combination of optical spectroscopy and machine learning to sort plastic waste.

In-process melt filtration

Melt filtration is a critical in-process step during plastics extrusion that removes solid contaminants like foreign materials, gels, and carbonized particles by forcing the molten polymer through a screen before it reaches the die[54]. A wide array of technologies exists to accomplish this, ranging from simple manual filters that require line stoppage for changes, suitable for low contamination, to advanced, continuous systems designed for handling more heavily contaminated post-consumer waste. These include backflush filters that automatically clean themselves, robust laser filters with scraper mechanisms, and continuous band filters. The selection of an appropriate system is dictated by the polymer type, the expected level of contamination, and required final purity, with a clear industrial trend towards continuous systems. Although they represent a higher initial investment, continuous filters are economically imperative for high-throughput recycling operations as they significantly reduce costly production downtime, making them a necessary component for efficiently processing variable post-consumer materials.

In-process devolatilization

Devolatilization, or degassing, is an important in-process technique during extrusion designed to remove unwanted volatile components - such as moisture, entrapped air, residual monomers, and degradation byproducts - from the polymer melt[55]. This is most commonly accomplished by incorporating vented sections in the extruder barrel where a vacuum is applied to a large, exposed surface area of the partially filled screw channel, facilitating the evaporation and extraction of these substances. The efficiency of this process, which is vital for reducing odors, preventing visual defects like bubbles, and improving mechanical properties, is influenced by factors like residence time under the vent, melt temperature, vacuum level, and the rate of melt surface renewal, with co-rotating twin-screw extruders generally offering superior performance due to their inherent mixing capabilities. Ultimately, the effectiveness of devolatilization hinges on the synergistic optimization of the screw design and temperature profile to maximize the removal of contaminants from recycled feedstocks, although specialized static systems may be employed for materials with exceptionally high solvent content

Additive-based quality improvement

To maintain the integrity of plastics during reprocessing and subsequent life cycles, stabilizers are widely incorporated[56]. As shown in Figure 8, stabilizers protect polymers during recycling based on their function and several challenges and issues persist. Antioxidants[57] counter oxidation: primary antioxidants (radical scavengers) like hindered phenols and amines (HALS) intercept free radicals, while secondary antioxidants (hydroperoxide decomposers) like phosphites neutralize hydroperoxides. UV stabilizers[58], present from the polymer's service life, protect against UV degradation, though some like carbon black can complicate NIR sorting. Acid scavengers/neutralizers[59,60] (e.g., metal soaps, calcium carbonate) are vital for polymers like PVC, neutralizing acidic byproducts (e.g., HCl) to prevent further degradation and equipment corrosion. While virgin plastics are stabilized for initial processing and service life, such stabilizers are generally consumed by the recycling point and need to be re-stabilized at additional cost to protect the vulnerable material against reprocessing. Some of the key issues are the impact of some stabilizers or their degradation products on recyclate appearance, safety (especially for food contact[61]), and sortability (e.g., interference of carbon black with NIR sorting[62]). Furthermore, stabilizer mixtures have antagonistic effects, their migration from recycled plastics poses a toxicity risk, their effectiveness over several recycling generations is poorly understood, and optimizing

them for application with heterogeneous, contaminated feed streams involve considerable expense and complexity.

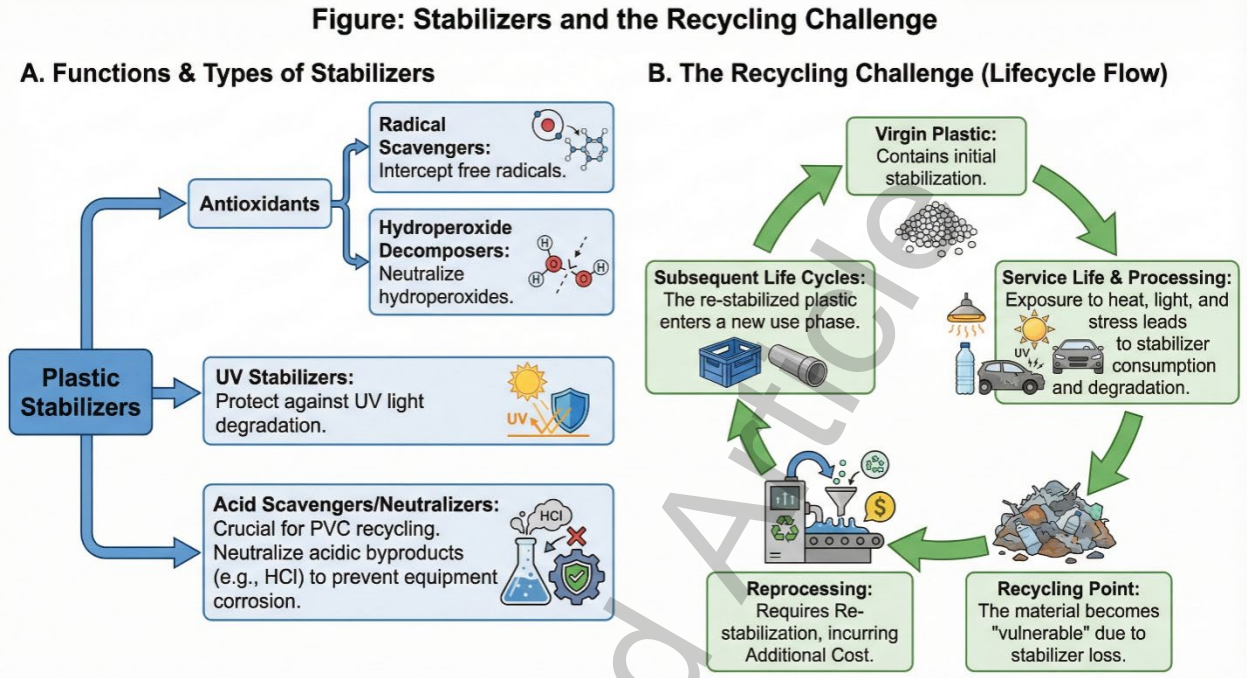

Figure 8. The function and challenges of additive-based quality improvement.

Antioxidants

Antioxidants (AOs) are vital for inhibiting thermo-oxidative degradation, which occurs when polymers are processed at high temperatures in the presence of oxygen, and during the service life of the plastic product. They function by interrupting the radical chain reactions that lead to polymer breakdown[63]. Primary antioxidants, such as sterically hindered phenols like Irganox 1010, function as radical scavengers that rapidly neutralize highly reactive polymer and peroxy radicals, thereby preventing the propagation of the degradation chain[64]. Complementing this action, secondary antioxidants work by decomposing unstable hydroperoxide intermediates into non-radical, stable products before they can break down and generate new radicals; common examples include organophosphites like Irgafos 168[65], which are effective during melt processing, and thioesters, which enhance long-term thermal stability. To achieve the most comprehensive protection, synergistic blends combining primary and secondary antioxidants are frequently

employed, as this approach leverages their different mechanisms to more effectively interrupt the entire oxidative degradation process.

For instant, functionalized mesoporous silica (MCM-41) loaded with Irganox 1076 has shown promise for improving the thermal stability of recycled PP[66]. Natural antioxidants from agro-wastes like grape pomace have also demonstrated some activity in stabilizing LDPE during reprocessing[67]. For recycled PET, phosphite antioxidants (e.g., bis(2,4-ditert-butylphenyl) pentaerythritol diphosphate) can significantly improve anti-oxidative performance and color stability[68]. For instance, in mixed HDPE/PP recyclates, a restabilization package with 0.1% primary antioxidant (AO-1), 0.1% secondary antioxidant (P-2), and 0.2% CaO as an acid scavenger was shown to significantly improve long-term thermal stability[69]. Phenolic antioxidants have also been evaluated for HDPE recyclate from water bottle caps intended for use in cross-linked pipes.

Acid scavengers

Acid scavengers are additives incorporated into polymers to neutralize acidic impurities or byproducts that can arise from various sources, including catalyst residues from polymerization, environmental exposure, or polymer degradation itself (e.g., HCl from PVC, carboxylic acids from PET hydrolysis or oxidation)[70]. If left unneutralized, these acidic compounds can catalyze further degradation reactions, leading to loss of polymer properties, discoloration, odor generation, and corrosion of processing equipment.

The most effective way to prevent this degradation is by adding thermal stabilizers[71], which function through two main, often complementary, mechanisms[72]. The first mechanism involves the stabilizer reacting with or replacing the unstable, labile chlorine atoms located at defect sites on the PVC chains. By passivating these active sites, the stabilizer prevents the initial dehydrochlorination reaction from starting, which inhibits the formation of the long polyene sequences responsible for initial color changes and discoloration[41]. This function is performed by various types of stabilizers, including metal soaps[73], organotins[74], and metal alkoxides[75], all of which can replace the labile chlorines. The second crucial mechanism is the absorption or neutralization of the HCl gas that is inevitably generated during processing. By scavenging this

HCl, stabilizers prevent it from auto-catalyzing further widespread degradation, thereby providing essential long-term thermal stability to the PVC material. Lead salts are particularly efficient HCl scavengers[76], as are organic stabilizers containing amino or imino groups, such as uracil derivatives. Because a single stabilizer rarely performs both functions optimally, commercial applications often rely on compounded systems, such as a synergistic blend of calcium and zinc metal soaps (Ca/Zn), to provide comprehensive protection against both initial and long-term degradation[77].

Light stabilizers

For recycled plastics intended for outdoor applications, protection against degradation caused by ultraviolet (UV) radiation from sunlight is essential to maintain aesthetic appearance and mechanical integrity over the product's lifespan.

Hindered Amine Light Stabilizers (HALS) and UV absorbers of the benzophenone or benzotriazole type are used in applications such as HDPE bottle crates, pipes, and pallets made from polyolefin mixtures[78]. Research has also explored the use of natural, bio-derived antioxidants like vitamin E and curcumin, which have shown protective capabilities comparable to or even exceeding their synthetic counterparts in certain studies[79]. By using these tailored stabilizer systems, the mechanical recycling of PE can produce a high-quality material, enabling its use in closed-loop systems and new, demanding applications

REACTIVE EXTRUSION: IN-SITU CHEMICAL MODIFICATION AND UPCYCLING

Reactive extrusion (REX) refers to processes where chemical reactions are intentionally carried out on polymeric materials directly within the extruder, as shown in Figure 9. The extruder acts as a continuous chemical reactor, providing the necessary conditions (temperature, pressure, mixing, shear) for these reactions to occur. This technology is a powerful tool for the "upcycling" of plastic waste, aiming to produce materials with new functionalities or improved properties rather than simply reprocessing them into lower-grade applications.

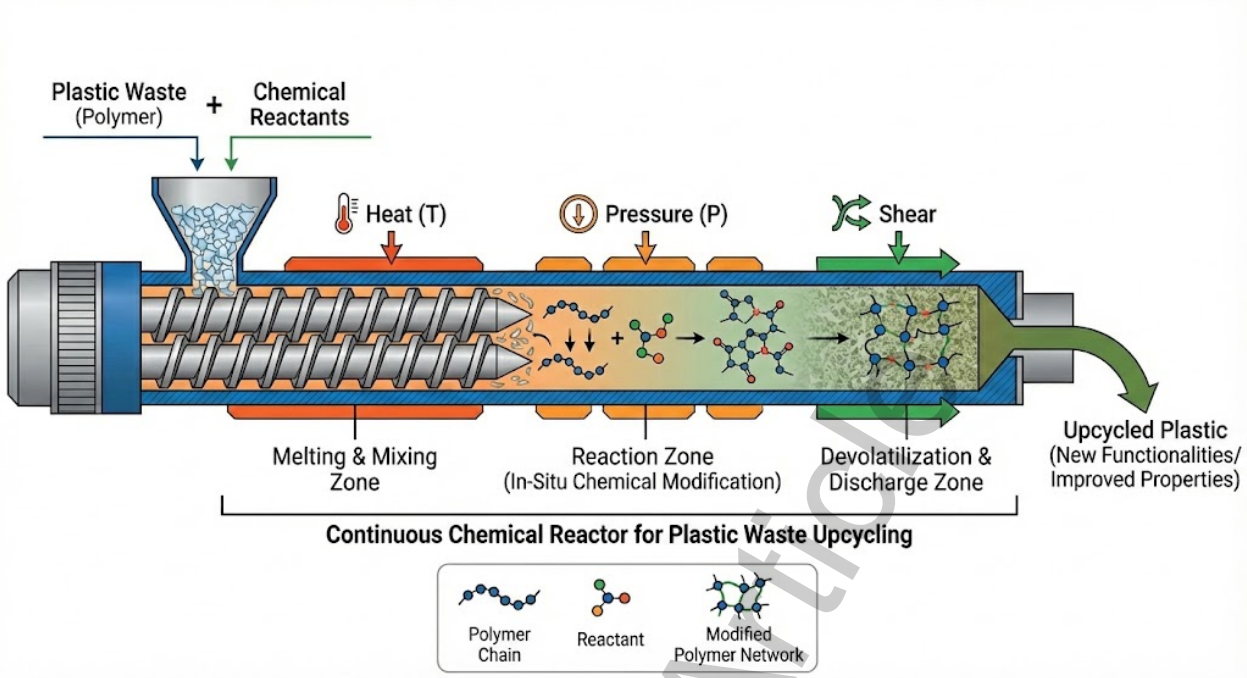

Figure 9. Schematic representation of Reactive Extrusion (REX) for plastic waste upcycling.

Chain extension for molecular weight restoration

Chain extension is a key REX strategy used to counteract the reduction in molecular weight (and associated properties like melt viscosity and mechanical strength) that occurs due to degradation during previous use and reprocessing. It involves reacting the degraded polymer chains with multifunctional additives (chain extenders) that can link two or more shorter chains together. A variety of chemical agents are used for polymer chain extension, with the choice depending on the polymer's chemistry, processing conditions, desired properties, and cost. These agents work by reacting with the terminal groups of polymer chains to increase their molecular weight and modify their properties.

Conventional chemical agents for polymer chain extension

The main conventional types include those based on epoxy, isocyanate, anhydride, and oxazoline functionalities[80].

Epoxy-based chain extenders are widely used commercially, with the Joncryl® ADR[81] series being a prominent example. Their strained epoxy ring reacts readily with the carboxyl and

hydroxyl end groups of condensation polymers like polyesters. They are crucial in improving the low melt strength and brittleness of PLA[82] and in restoring the molecular weight of recycled PET (rPET). For rPET, epoxy extenders like Joncryl® have demonstrated significant efficacy in reversing degradation. For instance, studies have shown that incorporating just 0.5-1.0% of a Joncryl® ADR-type chain extender during reactive extrusion can increase the intrinsic viscosity of rPET from a degraded 0.65 dL/g back to 0.80 dL/g, restoring it to near-virgin levels[83]. This restoration of molecular weight directly translates to improved mechanical performance, with reports of tensile strength increasing by up to 20% and impact strength improving significantly, making the recycled material suitable for more demanding applications[84]. However, the major drawback of these extenders is the toxicity concern associated with their glycidyl chemistry, which is a key driver for the development of safer alternatives.

Isocyanate-based compounds are another important class known for their very high reactivity[85]. The isocyanate group (-N=C=O) reacts efficiently with hydroxyl groups to form urethane linkages and with amine groups to form urea linkages, significantly increasing the polymer's molecular weight and viscosity[86]. A study showed that diisocyanates exhibited slightly higher and faster chain extension reactivity than a polymeric epoxidized extender in recycled PLA[87]. While effective at transforming brittle recycled materials into more ductile ones, their application is severely limited by critical drawbacks. The most significant issue is toxicity, as many isocyanates are respiratory sensitizers and suspected carcinogens[88].

Anhydride-based extenders, such as pyromellitic dianhydride (PMDA), react with hydroxyl or amine end groups through a ring-opening mechanism. PMDA is a highly functional agent capable of significantly increasing the melt viscosity and toughness of polyesters[89]. In PLA systems, PMDA reacts with hydroxyl end groups to generate carboxyl groups, which can then be targeted by epoxy-based CEs in synergistic chain extension strategies[90]. However, a critical limitation is that its reaction can form water as a byproduct, which can accelerate the hydrolytic degradation of polymers like PET. This, along with a complex reaction mechanism, can make the process challenging to control.

Oxazoline-based compounds represent a more specialized class of chain extenders that react primarily with carboxyl end groups. Their main advantage is that the reaction proceeds without forming any detrimental by-products, leading to cleaner processing. A study by Pasanphan *et al.*[91] detailed the use of PBO as a chain extender for recycled PET, demonstrating a significant increase in intrinsic viscosity, indicative of molecular weight enhancement. While effective in reactive extrusion for polymers like rPET, their use is often limited by their high cost and the less extensive variety of commercially available options compared to epoxy or isocyanate types.

The comparative overview of conventional polymer chain extenders is shown in Table 3. A simplified reactivity hierarchy, isocyanates are generally the most reactive, followed by epoxies and anhydrides, and then oxazolines, although this order is highly dependent on specific reaction conditions and chemical structures. These CEs also exhibit distinct selectivity: oxazolines are highly specific to carboxyl groups, whereas epoxies react with both carboxyl and hydroxyl groups, isocyanates favor amine and hydroxyl groups, and anhydrides primarily target hydroxyl and amine functionalities. A key advantage of oxazolines is their reaction mechanism, which produces no by-products, unlike isocyanates that can release CO_2 or certain anhydrides that generate water, potentially causing polymer degradation. Commercially, epoxy and anhydride CEs are widely available and cost-effective, whereas oxazolines tend to be more expensive and specialized.

Table 3. Comparative overview of conventional polymer chain extenders

Type	Reactive Functional Group(s)	Primary Target Polymer End Groups	Typical Polymer Systems	Resulting Linkage(s)	Typical Effect on Architecture	Advantages	Disadvantages
Epoxy-GMA based	Epoxy (Glycidyl)	-COOH, -OH, -NH2	PLA, PET, PA, PC, Blends	β-hydroxy ester, Ether, β-hydroxy amine	Branched	Good reactivity, Cost-effective, Widely available, Versatile	Glycidyl toxicity, Uncontrolled side reactions (new -OH), Can reduce crystallinity

Diisocyanate	Isocyanate (-NCO)	-OH, -NH2 (primary); -COOH (secondary)	PLA, PET, PA, PU	Urethane, Urea, Amide	Linear Branched	High reactivity, Rapid MW increase	High toxicity, Moisture sensitive, Product discoloration, Difficult to control reactivity, Potential for chain scission
Dianhydride (e.g., PMDA)	Cyclic Anhydride	-OH, -NH2	PET, PLA, PA (TPAE)	Ester + new -COOH, Amide + new -COOH	Branched/Crosslinked (PMDA)	High reactivity (PMDA), Can generate reactive -COOH for further modification	Byproduct (e.g., water with PMDA in PET causing degradation), Complex reactions, Potential for brittleness if over-reacted
Bisoxazoline (e.g., PBO)	Oxazoline	-COOH	PET, PLA	Ester-amide	Linear	No by-products, Good selectivity for -COOH, Suitable for reactive extrusion	Higher cost, Limited availability, Specificity for -COOH may require polymer pre-modification

Recent advances in chain extender chemistries and materials

In response to the toxicity concerns associated with conventional chain extenders like glycidol methacrylate (GMA)[92], recent research has focused on developing safer and more sustainable alternatives. A significant advancement involves glycidol-free epoxy-functional methacrylates, such as 9-(oxiran-2-yl)nonyl methacrylate (EAT), which, when grafted onto a PCL backbone,

demonstrate enhanced mechanical properties in PLA comparable to commercial CEs but with no observable cytotoxicity[93]. Concurrently, the field of polyurethanes is being transformed by bio-derived chain extenders from precursors like lignocellulosic biomass and cashew nutshell liquid[94]. For instance, a rationally designed eugenol-based glycol dimer (EGD) imparts exceptional self-healing and antioxidant properties to PU elastomers[95], while sulfonated cardanol derivatives improve the stability of waterborne polyurethane dispersions. This trend towards utilizing renewable resources is further exemplified by epoxidized cardanol, which acts as an effective compatibilizer for PLA/PBAT blends[96]. These developments signal a paradigm shift towards a "safe-and-sustainable-by-design" philosophy, where the development of novel chain extenders holistically integrates performance metrics with rigorous assessments of cytotoxicity, lifecycle costs, and overall environmental impact.

The pursuit of greener chemical technologies includes eliminating organic solvents to reduce volatile organic compound (VOC) emissions, operational costs, and process complexity. While the application of commercial chain extenders (CEs) through reactive extrusion is already an inherently solvent-free process that uses the molten polymer as the reaction medium, recent innovations now focus on the solvent-free synthesis of the CEs themselves[97]. A notable example is a patented method[98] using aqueous polymerization followed by extrusion to produce epoxy-functional CEs for recycled and biodegradable plastics, enhancing the technology's overall environmental credentials. This trend is complemented by advancements in enzyme-catalyzed polymer functionalization[99], which are increasingly performed under solventless conditions, a critical development for sensitive applications like biomaterials where solvent residues are unacceptable.

As new polymers are developed, chain extension and related techniques are adapted to optimize their performance. For emerging bio-polyesters like Poly(ethylene furanoate) (PEF)[100], initial modification strategies focus on significant property enhancements rather than simple molecular weight restoration. This is achieved through advanced methods such as reactive compatibilization with maleated polymers to dramatically improve toughness, or by synthesizing block copolymers (e.g., PEF-PCL)[101] to create novel architectures. In advanced polyurethanes, the trend is towards "smart" chain extenders that are engineered as functional building blocks; for example, eugenol-

derived extenders impart self-healing and antioxidant properties, while sulfonated extenders improve the stability of waterborne dispersions[102]. Furthermore, chain extenders play a specialized role in the recycling of complex materials like polymer nanocomposites, where they are added during reprocessing to counteract matrix degradation and maintain mechanical properties. This demonstrates an evolution where techniques progress from complex macromolecular engineering for new polymers to the use of conventional chain extenders for property restoration in mature or recycled materials.

Critical comparative analysis of chain extension strategies

While the primary objective of all chain extenders is molecular weight restoration, a critical analysis of the literature reveals significant trade-offs regarding reactivity kinetics, dosage efficiency, and safety profiles. Isocyanate-based extenders represent the high-reactivity end of the spectrum. Due to the rapid kinetics of the -NCO group, they can theoretically achieve restoration at lower dosages than other chemistries. However, this high reactivity comes at a cost: it often results in a broad molecular weight distribution (MWD) and poses significant process control challenges, including a high risk of gelation if local concentrations are not managed precisely. Furthermore, the inherent toxicity of isocyanates - many of which are respiratory sensitizers - remains a critical barrier to their widespread adoption in sustainable packaging.

In contrast, epoxy-based multifunctional extenders (e.g., Joncryl® ADR) have emerged as the industrial standard due to their balanced performance profile. Quantitative studies have demonstrated that a dosage of 0.5-1.0 wt% is typically sufficient to increase the intrinsic viscosity (IV) of recycled PET from a degraded state of 0.65 dL/g back to 0.80 dL/g. This rheological recovery correlates directly with mechanical performance, with reports of tensile strength increasing by up to 20% following reactive extrusion. While effective, they are not without limitations; unlike isocyanates, epoxies can participate in side reactions that may reduce crystallinity if not carefully controlled.

Alternative chemistries offer specialized solutions for niche applications but face economic hurdles. Anhydride-based extenders (e.g., PMDA) are capable of generating high melt viscosities through extensive branching, but this often leads to a trade-off in ductility, rendering the material

brittle if the degree of modification is too high. Conversely, Bisoxazolines provide superior control due to their high selectivity for carboxyl end-groups without generating volatile by-products. However, their cost-efficiency is significantly lower than that of epoxies; achieving comparable IV recovery often requires higher molar equivalents, making them less economically viable for low-margin commodity recycling despite their "cleaner" chemistry.

Ultimately, the selection of a chain extension strategy is a compromise between performance, safety, and cost. Isocyanates offer the highest reactivity but pose toxicity risks; epoxies provide the most reliable restoration of mechanical properties for polyesters; and bisoxazolines offer the highest purity for sensitive applications but at a premium cost.

Compatibilization of mixed plastic streams

Most plastics exhibit thermodynamic incompatibility. Upon melt blending, they undergo phase separation, resulting in materials with inferior interfacial adhesion.. Compatibilization is a process that addresses this deficiency. It involves adding a compatibilizer - an agent that acts as a bridge or "polymeric surfactant" - to help the different plastics bond together. This improves adhesion and enhances the overall performance and strength of the recycled material.

Several strategies have been developed to compatibilize immiscible polymer blends, broadly categorized into non-reactive, reactive, and emerging approaches. Non-reactive compatibilization involves the addition of pre-synthesized copolymers, typically block or graft copolymers, to the immiscible polymer blend during melt processing. Ethylene/propylene copolymers (EPR) are well-known compatibilizers for blends of polypropylene (PP) and low-density polyethylene (LDPE)[103]. Styrenic block copolymers like styrene-butadiene-styrene (SBS) or styrene-ethylene-butylene-styrene (SEBS) are commonly used for blends involving polyolefins and polystyrene (PS) or other styrenic polymers[104]. For PE/PP blends, various olefin block copolymers (OBCs), ethylene-propylene random copolymers (EPR), and SEBS have been investigated as effective non-reactive compatibilizers[105]. Reactive compatibilization involves the in-situ formation of copolymers (typically graft or block copolymers) directly at the interface between immiscible polymers during melt processing. A widely studied example is the use of maleic anhydride-grafted polyolefins (e.g., PP-g-MAH, PE-g-MAH) to compatibilize blends of polyolefins with polar

polymers like polyamides (e.g., PA6, PA66) or polyesters (e.g., PET)[106,107]. The anhydride groups on the modified polyolefin can react with the amine or hydroxyl end-groups of the polyamide or polyester, respectively, forming graft copolymers at the interface[108].

Beyond traditional non-reactive and reactive methods, several innovative strategies are being explored to address the challenges of compatibilizing complex mixed plastic streams. Nanoparticles like nanoclays, carbon nanotubes, or nanosilica can act as compatibilizers[28,109-111]. They migrate to the interface between immiscible polymers, creating a physical barrier that reduces interfacial tension and prevents phase separation, much like solid particles in a Pickering emulsion. Their success depends on their size, shape, and surface chemistry. Another innovative approach uses cross-linkers that form reversible bonds between different polymer chains[50,112]. Under processing heat and shear, these bonds can break and reform, allowing the material to flow while still bridging the polymer phases. This improves both compatibility and the final mechanical properties.

SCREW EXTRUSION AS AN ENABLER IN CHEMICAL DEPOLYMERIZATION PROCESSES

Chemical recycling encompasses a range of advanced technologies that depolymerize plastics into their constituent monomers, oligomers, or basic chemical feedstocks[13]. These products can then be used to synthesize new virgin-quality plastics, fuels, or other valuable chemicals, effectively closing the material loop. This approach is particularly promising for handling plastic waste streams that are difficult or impossible to recycle mechanically, such as mixed plastics, multi-layer packaging, or heavily contaminated materials, thus complementing mechanical recycling efforts.

In this evolving landscape, screw extruders, especially twin-screw extruders (TSEs), are finding increasingly sophisticated roles beyond simple melt processing. They are being employed as highly efficient continuous chemical reactors and as critical pre-treatment systems for various chemical recycling pathways.

Pyrolysis: feedstock preparation and integrated processing

Pyrolysis is a thermochemical process that decomposes plastics at elevated temperatures (typically 300-900°C) in an oxygen-deficient environment to produce a mixture of pyrolysis oil (a synthetic crude oil), non-condensable gases (syngas), and a solid char residue[113]. Screw extruders, predominantly twin-screw systems, play a crucial role in the pre-treatment of plastic waste feedstock for pyrolysis units[114]. Their functions include melting the plastic waste, homogenizing it, devolatilizing moisture and other volatile impurities, and continuously feeding a consistent, pre-heated melt to the pyrolysis reactor. Research indicates that extrusion pre-treatment can significantly alter the thermal decomposition dynamics of plastics[115]. For polyethylene (PE), pre-treatment in a co-rotating twin-screw extruder at elevated temperatures (e.g., 450°C for 2 minutes) has been shown to modify reaction kinetics and influence product yields during subsequent pyrolysis[116]. While the overall chemical composition of the product stream might remain relatively stable for a given polymer, the rate at which these products are formed and their relative proportions can be affected. Altered kinetics could lead to more efficient reactor utilization or provide pathways to selectively enhance certain product fractions. However, the extent of this influence can be feedstock- and condition-dependent. In studies involving the co-pyrolysis of coal and plastic (LDPE, PP) mixtures that were first compounded into extrudates, the yields of char and condensable products during slow pyrolysis were found to closely follow an additive model based on the pyrolysis of the individual raw materials[117]. This suggests that under those specific conditions (slow heating, particular material blend), the extrusion process primarily served as a method for homogenization and physical shaping of the feedstock, rather than inducing significant synergistic chemical changes that dramatically altered the bulk product yields from what would be expected from their individual components.

Screw extruders can be designed and operated not just as pre-treatment devices but as continuous reactors where pyrolysis, or at least the initial, significant stages of thermal cracking, occurs. By configuring specific temperature profiles along the barrel, incorporating specialized mixing and reaction zones, and controlling residence time, extruders can achieve targeted levels of polymer degradation. This integration of reaction within the extruder embodies the principles of process intensification, offering benefits in terms of reduced equipment footprint and potentially improved energy efficiency. For instance, a patent[118] describes a screw conveyor within a reaction chamber for rubber pyrolysis, where the screw provides both transport and influences heat exposure.

Depolymerization of condensation polymers by solvolysis

Depolymerization assisted by SE has emerged as a highly effective and rapid method for the chemical recycling of PET, demonstrating a high technology readiness level, particularly for glycolysis and hydrolysis (Figure 10). In a continuous process using a twin-screw extruder, PET waste including bilayer PET/PE material, can be successfully and efficiently performed[119]. The process achieves a high degree of depolymerization (over 97%) within very short residence times in the order of minutes, yielding the monomers ethylene glycol (EG) and the salt of terephthalic acid (TA). One approach utilized a co-rotating twin-screw extruder where PET hydrolysis was achieved by injecting high-pressure saturated steam directly into the extruder[120]. This process yielded low molecular weight products even at short residence times, indicating high depolymerization rates. Optimal conditions were found at relatively low screw speeds and water/PET ratios. Beyond successfully depolymerizing pure and textile waste PET under optimized conditions, Ng *et al.*[121] demonstrated the upcycling of the extrudates into high-value, reprocessable vitrimer films acting as recyclable adhesives (Figure 10b).

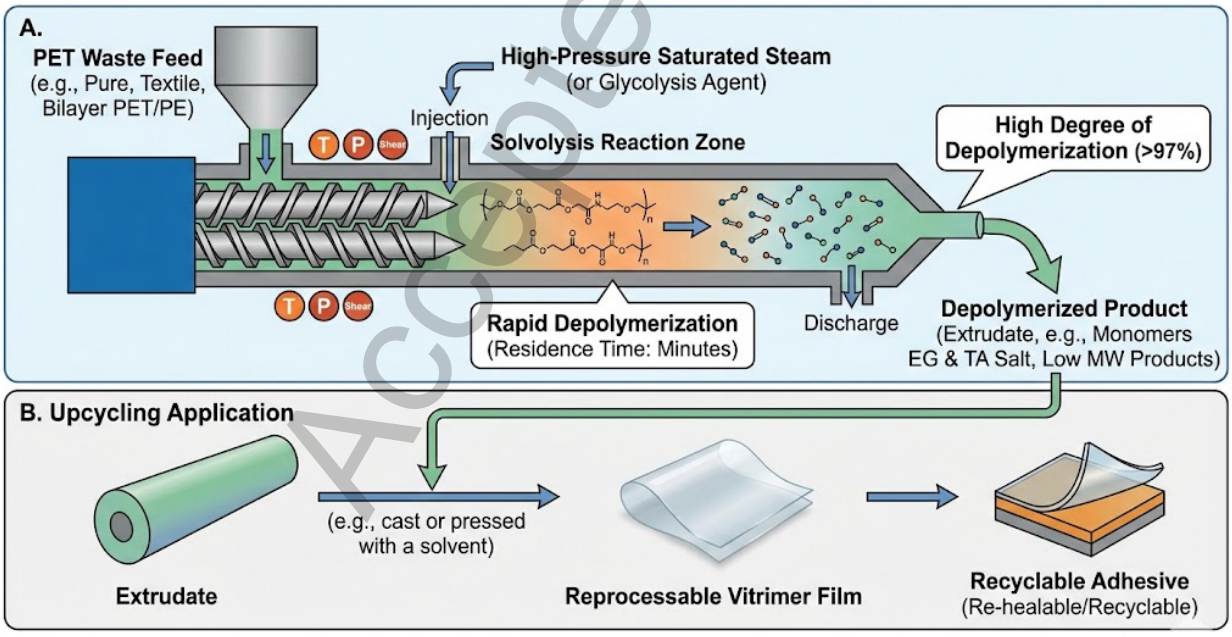

Figure 10. Continuous depolymerization of PET waste vias solvolysis in a twin-screw extruder an dupcycling.

COMMERCIAL LANDSCAPE: TECHNOLOGICAL INNOVATIONS AND REAL-WORLD CONSTRAINTS

The industrial application of screw extrusion has evolved from simple reprocessing into highly specialized, integrated systems. Rather than standard off-the-shelf equipment, the current landscape is defined by purpose-built innovations designed to tackle specific recycling hurdles.

Innovations in mechanical recycling

Enhanced Feeding and Filtration: Handling low-bulk density recyclates (e.g., films, fibers) is a persistent challenge. Technological solutions like active side-feeding systems (e.g., Coperion's ZS-B MEGAfeed) utilize vacuum-assisted screws to force light materials into the extruder, effectively increasing throughput for light-weight flakes without requiring energy-intensive pre-compaction. Simultaneously, the integration of continuous melt filtration and compounding into single steps (e.g., Coperion ZSK FilCo) allows for the processing of heavily contaminated PCR streams while significantly reducing energy consumption compared to two-step lines[122].

Decontamination for Food-Contact Quality: To meet stringent regulatory standards (FDA/EFSA), manufacturers have developed systems that combine extrusion with vacuum-assisted solid-state polycondensation (SSP). Technologies such as EREMA's VACUNITE®[123] and Starlinger's recoSTAR[124] PET art integrate pre-drying, extrusion, and crystallization in a continuous line. These systems minimize thermal stress and residence time, effectively removing volatile contaminants and restoring Intrinsic Viscosity (IV) to levels suitable for bottle-to-bottle recycling.

Integrated Shredding and Direct Extrusion: For post-industrial scrap, systems that couple shredding directly with the extruder feeder (e.g., NGR's S:GRAN, Starlinger's recoSTAR)[124,125] eliminate the need for separate grinding steps. This "zero-scrap" approach allows for the immediate reintroduction of production waste (e.g., woven sacks, films) into the manufacturing cycle, maximizing material efficiency.

Enablers for chemical recycling

In chemical recycling, twin-screw extruders are increasingly utilized as continuous reactors and pre-treatment units. Industrial-scale operations, such as Indaver's facility in Antwerp, employ extruders to rapidly melt and devolatilize mixed polyolefins/PS waste before feeding them into depolymerization reactors. This pre-treatment ensures a homogeneous, moisture-free melt, which is critical for the stability of downstream cracking processes. Similarly, high-torque extruders are being deployed to drive solvolysis reactions for PET, utilizing the extruder's mixing capabilities to maximize catalyst contact and reaction kinetics in a continuous flow.

Critical assessment: advantages and limitations

The primary benefit is quality restoration. Advanced integrated systems can produce food-grade pellets that rival virgin resin, closing the loop for high-value applications. Furthermore, process intensification (combining shredding, melting, and filtering) yields substantial energy efficiency gains, with some systems reporting >50% energy savings compared to conventional multi-step reprocessing.

The most significant barrier is economic feasibility[126]. These specialized lines command a high capital expenditure (CAPEX), making them viable primarily for large-scale operations. Operationally, even advanced filtration systems have limits; they are highly sensitive to specific contaminants like PVC, which can degrade to release corrosive HCl, damaging the expensive screw/barrel metallurgy. Finally, the complexity of operation requires skilled personnel, as precise control over vacuum levels, residence times, and shear rates is mandatory to prevent material degradation during these intensive processes.

CONCLUSION AND OUTLOOK

Recapitulation of screw extrusion's impact on mechanical and chemical recycling

Screw extrusion has unequivocally established itself as a cornerstone technology in the global effort to manage plastic waste. In mechanical recycling, it serves as a foundational process, transforming sorted and cleaned plastic waste into reusable pellets or directly into new products. Its ability to melt, mix, homogenize, and filter makes it indispensable for converting diverse waste streams into consistent, marketable secondary raw materials. The selection between single-screw and twin-screw architectures is a fundamental determinant of process efficacy. Equally critical is

the integration of advanced auxiliary systems, such as specialized feeders, melt filters, and devolatilization units, which enable the processing of varied and contaminated feedstocks.

Beyond its established role in mechanical recycling, screw extrusion is rapidly emerging as a vital enabling technology in the burgeoning field of chemical recycling. Twin-screw extruders, in particular, are being increasingly leveraged as continuous chemical reactors or highly efficient pre-treatment systems. They facilitate processes like pyrolysis by preparing a homogeneous, pre-heated melt and enabling catalyst incorporation, and they drive solvolysis reactions (e.g., PET glycolysis) with significantly enhanced kinetics and continuous operation compared to traditional batch methods. This dual applicability underscores the versatility and adaptability of screw extrusion technology.

Future perspectives: emerging trends and research needs

The future of screw extrusion in plastic recycling is evolving beyond conventional methods to address persistent challenges like high energy consumption and material degradation. This evolution is unfolding across several interconnected fronts, from direct technological upgrades and enhanced process intelligence to expanding the scope of recyclable materials and meeting stringent regulatory demands.

AI-driven process intelligence and generative design

The integration of Artificial Intelligence (AI) offers transformative potential for plastic recycling by moving beyond simple automation to predictive, self-optimizing systems. Future research should prioritize the development of "soft sensors" - machine learning algorithms trained on historical process data (torque, pressure, temperature) - that can function as virtual rheometers. These models estimate critical quality parameters like melt viscosity or contaminant levels in real-time, enabling the extruder to instantly adjust processing conditions to compensate for the inherent variability of post-consumer feedstock. Beyond operations, AI can revolutionize equipment engineering through "generative design," where algorithms simulate millions of screw configurations to identify non-intuitive element arrangements that maximize mixing efficiency for specific waste blends. Furthermore, by continuously analyzing vibration and torque signatures, AI models can facilitate predictive maintenance, detecting early signs of screw wear or screen pack

clogging before catastrophic failure occurs, thereby significantly improving the operational stability and economic viability of recycling plants.

Alternative energy input mechanisms

Conventional screw extrusion relies heavily on viscous dissipation (shear heating) to melt polymers. However, this mechanical shear often causes unavoidable thermo-mechanical degradation, limiting the number of recycling cycles a material can endure. To overcome this, future technological development should focus on alternative energy input mechanisms that decouple melting from shearing. By utilizing dielectric heating, the microwave-assisted extrusion offers volumetric heating capabilities, allowing for rapid and uniform melting at lower overall temperatures. Research is needed to scale this technology from pilot to industrial levels and to understand the dielectric properties of heterogeneous waste blends. Supercritical Fluid-Assisted Processing offer another possibility. The injection of supercritical fluids (e.g., $scCO_2$) acts as a reversible plasticizer, significantly reducing melt viscosity and allowing for processing at lower temperatures. Furthermore, $scCO_2$ can serve as a solvent for stripping contaminants. Future work should optimize the injection protocols and screw geometries required to maximize this dual plasticization-decontamination effect.

Advanced decontamination for high-value applications

As regulations for food-contact materials tighten, the removal of Non-Intentionally Added Substances (NIAS) and persistent odors has become a primary technical hurdle. Standard vacuum devolatilization is often insufficient for these micropollutants. The industry requires a new generation of "functionalized extrusion" techniques. This includes the development of specific stripping agents (e.g., water, inert gases) and the incorporation of porous adsorbents (e.g., zeolites, activated carbon) directly into the compounding step. Research must rigorously quantify the mass transfer kinetics of these contaminants to design screw elements that maximize surface renewal and diffusion rates without compromising throughput.

Systemic standardization and design for recycling

Finally, the role of the extruder must be contextualized within the broader circular economy. A major barrier to the adoption of hybrid recycling models (mechanical-chemical) is the lack of

standardized Life Cycle Assessment (LCA) data. The scientific community must establish consistent system boundaries to accurately compare the environmental footprint of mechanical reprocessing versus chemical depolymerization. Additionally, the concept of "Design for Recycling" must evolve into a data-driven feedback loop. Insights gained from the extrusion process - such as filter clogging rates caused by specific labels or the degradation impact of certain additives - should directly inform the design of upstream packaging, thereby minimizing the entry of problematic materials into the waste stream.

DECLARATIONS

Authors' contributions

Zixian JIA: Writing - review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Lin GAO, Writing - review & editing, Visualization, Validation, Investigation, Formal analysis. Lijiao QIN, Writing - review & editing, Investigation. Shuandi HOU: Writing - review & editing, Resources, Project administration, Funding acquisition. Guohua HU: Writing - review & editing, Resources, Project administration, Funding acquisition.

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Conflicts of interest

Zixian Jia, Lin Gao, Lijiao Qin and Shuandi Hou are affiliated with SINOPEC(Dalian) Research Institute of Petroleum and Petrochemicals Co.,Ltd. Guo-hua Hu declares that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

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