Mechanical Recycling of PET Beverage Bottles: Challenges of Property Retention and Chain Degradation Across Multiple Processing Cycles

Shameem Kazmi[1], David Jones[2], Mohammed Shah[3]
Department of Materials, Loughborough University, Leicestershire, UK
https://orcid.org/0000-0003-2968-1906

Abstract

One of the pillars of Circular Economy and sustainable packaging in the global plastics industry is recycling polyethylene terephthalate (PET) beverage bottles. Recycling cycles of polymer chains pose real problems regarding polymer chain degradation, decreasing intrinsic viscosity (IV), and progressive crystallinity changes, all of which harm material performance. This paper offers a detailed analysis of mechanical recycling systems and their impact on PET's structural, thermal, and mechanical properties through various reprocessing cycles. Industrial extrusion and injection-moulding processes were simulated in the laboratory, and intrinsic viscosity, differential scanning calorimetry, tensile and impact testing, and spectroscopy were used to aid understanding of degradation mechanisms. Among the important results reported are the following: Polymer chain scission significantly decreases molecular weight, and crystallinity increases embrittlement and decreases toughness. Mechanical properties (tensile strength, elongation at break, impact resistance) show significant reductions between cycles, with a corresponding drop in thermal stability and reduced resilience in processing. The research also determines essential obstacles to closed-loop recycling, such as thermo-oxidative degradation, yellowing, haze formation, and barriers to attaining the quality of beverages because of regulatory and contamination restrictions. Circularity implications imply that mechanical recycling should not be solely relied upon to support endless bottle-to-bottle cycles, and it may need to be combined with virgin PET or other chemical recycling approaches to ensure product quality. The paper highlights the extreme significance of industry-wide actions, including design-to-recycle principles, optimisation of feedstock quality, and the development of new reprocessing technologies. This research also contributes to understanding PET degradation mechanisms, which can inform practical progress to increase the lifecycle of beverage-grade PET and advance the goals of sustainable plastics management.

Keywords: Mechanical PET Recycling, Polymer Chain Degradation, Intrinsic Viscosity Reduction, Crystallinity in Recycled PET, Beverage-Grade PET Sustainability, Closed-Loop Circularity

1. BACKGROUND AND RATIONALE

The most popular plastic to be used in the manufacturing of beverage bottles is polyethylene terephthalate (PET) because of its desirable balance of physical and chemical characteristics. PET has become the material of choice in the packaging of water, carbonated soft drinks, and an expanding line of functional beverages due to its optical clarity, lightness, and mechanical strength, coupled with good resistance to moisture and gases (He, Wei, Liu, and Xue, 2015; Saeed, Eltahir, Xia, and Yimin, 2015). The broad adoption of PET, however, has posed mounting challenges to waste management and resource efficiency, especially in the face of a global push towards the models of a circular economy (Bocken, de Pauw, Bakker, and van der Grinten, 2016; Haupt, Vadenbo, and Hellweg, 2017; Niero & Hauschild, 2017; Linder, Sarasini, and van Loon, 2017). The main path to PET circularity in the beverage industry is mechanical recycling due to its comparatively simple procedure that includes gathering, cleaning, shredding, and remoulding the material into granules (Vadicherla, Saravanan, and Muthu, 2015; Urbinati, Chiaroni, and Chiesa, 2017). Although this sounds good in theory, the mechanical recycling route is limited because the polymer itself is inherently vulnerable to the effects of degradation phenomena during the reprocessing process. Thermal, mechanical, and hydrolytic stresses are added every extrusion/moulding step and cause chain scission, reducing the intrinsic viscosity (IV) and molecular weight (Itim & Philip, 2015; Negoro et al., 2016). These processes are frequently accompanied by crystallinity growth and ductility and toughness decrease, which impairs the mechanical soundness and the ability to act as a barrier in recycled PET products (Strain, Wu, Pourrahimi, Hedenqvist, Olsson, and Andersson, 2015).

The issue of property retention through the several recycling cycles has been well documented. PET fibres and films that are recycled demonstrate the variations in tensile strength and elongation, whereas bottle-grade PET is susceptible to yellowing, haze, and loss of transparency because of structural rearrangements of polymer chains (Wheeler et al., 2016; Gewert, Plassmann, and Macleod, 2015). Studies investigating chain extenders, compatibilisers, and hybrid composites have met these deficiencies, including PET mixed with hyperbranched polyesters (Saeed et al., 2015; Kurniasih, Keilitz, and Haag, 2015). Alternative uses of recycled PET have also been considered by others, such as civil engineering (Marthong & Marthong, 2015), paving materials (Miguel, Santamaría-Cuellar, Contreras-Santos, Guerrero-Garcia, and Hernandez-Alcantara, 2015), and functional membranes to perform filtration (Strain et al., 2015). These strategies aim to heroically use PET waste products in high-value processes and avoid the deterioration of material performance. Outside the laboratory scale, scientists have been applying methods of modelling to forecast degradation routes and recycling results, such as using machine learning and data-driven models for materials science tasks. The research in predictive scoring and risk modelling demonstrates the importance of sophisticated algorithms to handle the issues of opacity, non-linearity, and multi-factorial effects in complex institutions

(Beque & Lessmann, 2017; Bhatia, Sharma, Burman, Hazari, and Hande, 2017; Burrell, 2016; Shi & Xu, 2016; Koutanaei, Sajedi, and Khanbabaei, 2015). Similar models would be modified to predict the behaviour of PET chains to degrade, recycling measures, and to trade off quality, cost, and environmental effects. Likewise, performance indicator systems designed in waste management and circular economy measurements (Pauliuk, Kondo, Nakamura, and Nakajima, 2017; Saleh, Annuar, and Simarani, 2017) offer an example of the assessment of the recycling systems in a holistic manner.

Concurrently, controlled-environment polymer degradation studies have also offered valuable mechanistic understanding of chain breakage and structural evolution including sonochemical depolymerisation and ultrasound-assisted scission degradation (Gogate and Prajapat, 2015; Prajapat and Gogate, 2016, 2017; Prajapat, Subhedar, and Gogate, 2016; Yan, Wang, Ma, and Wang, 2016; Prajapat and Gogate Although many of these studies have been carried out on other polysaccharides, or model polymers, these results emphasise the similarities in the knowledge about how intensifying the process can induce faster degradation phenomena, which directly applies to the development of more robust PET recycling schemes.

Against these considerations, recycling of PET bottles used for drinks offers a paradox: on the one hand, mechanical recycling is the best possible way to achieve material circularity in the packaging sector; on the other hand, the nature of the polymer to collapse into chain scission and deterioration of properties under repeated processing cycles impairs its sustainability claim. To overcome this challenge, the challenge will call upon the combination of materials science, process optimisation, the notion of the circular economy, and even the methods of data-driven modelling, in order to make sure that PET can remain a functional and recyclable packaging solution in the long term (Wagoner & Foegeding, 2017).

2. STUDY OBJECTIVES

Polyethylene terephthalate (PET) beverage bottle recycling has emerged as a high-priority field in materials science and sustainability research, especially with the persistent increase in the need to find eco-friendly packaging solutions. Mechanical recycling is considered the most feasible path to recovering PET due to its comparatively low price and the fact that such processing facilities already exist (Gogate & Prajapat, 2015; Prajapat and Gogate, 2015, 2016). However, it is confirmed that after being subjected to several reprocessing cycles, PET also experiences gradual alterations in structural and mechanical integrity, which makes it questionable whether the material could be viable in closed-loop applications (He et al., 2015; Itim & Philip, 2015; Negoro et al., 2016). These changes have not only been applied to performance in beverage packaging but also to the broader concepts of food-contact safety, regulatory compliance, and circular economy alignment (Bocken et al., 2016; Haupt, Vadenbo, and Hellweg, 2017; Linder, Sarasini, and van Loon, 2017; Urbinati, Chiaroni, and Chiesa, 2017).

The current research aims are organised in this manner, and three main themes are identified: the review of property retention in recycled PET, the discovery of degradation mechanisms, and the review of implications to food-contact safety and regulation. The objectives are detailed in the succeeding subsections.

2.1 Evaluation of Property Retention Across Recycling Cycles

The first is to establish the impacts of repeated mechanical recycling on the structural, thermal, and mechanical characteristics of PET beverage bottles. Previous studies demonstrated that tensile strength, glass transition temperature, and elongation at break change repeatedly with repeated extrusion and remelting, primarily because of chain scission and crystallinity changes (Saeed et al., 2015; Strain et al., 2015; Wheeler et al., 2016). These variations are crucial to understand how many rotations PET can endure without losing its appropriateness in beverage packaging purposes (Itim & Philip, 2015; Negoro et al., 2016).

2.2 Identification of Degradation Mechanisms

The second aim is to determine the degradation mechanisms that limit the reusability of PET in closed-loop beverage packages. As key routes of molecular deterioration in PET, hydrolysis, thermal oxidation, and transesterification have been identified (Gewert, Plassmann, and Macleod, 2015; Yan, Wang, Ma, and Wang, 2016; Saleh, Annuar, and Simarani, 2017). Overall, these processes decrease molecular weight and brittle nature, which limits the possibility of recycling in the end (Prajapat, Subhedar, & Gogate, 2016). The accumulating branching and chain scission with each processing cycle also gradually departs the resulting material from the performance requirements of food-grade packaging (Wheeler et al., 2016).

2.3 Implications for Food-Contact Safety and Regulatory Compliance

The third goal is to evaluate what mechanical recycling means to food-contact safety and regulatory compliance. The fact that PET bottles are primarily used with liquids implies that the migration behaviour and contamination threats should be thoroughly investigated to guarantee consumers' safety (Marthong & Marthong, 2015; Miguel et al., 2015). Consistent with the models of a circular economy, the safety of recycling is increasingly requested to be verified by regulators, which is often performed with the application of performance measures and predictive models (Haupt et al., 2017; Niero & Hauschild, 2017; Pauliuk, Kondo, Nakamura, and Nakajima, 2017). In this aspect, data-driven techniques, initially developed in other fields, including credit risk modelling and machine learning strategies (Beque & Lessmann, 2017; Bhatia et al., 2017; Burrell, 2016; Koutanaei, Sajedi, and Khanbabaei, 2015; Shi & Xu, 2016), would provide a good analogy to predict the patterns of PET degradation and guide the process of safety evaluation.

On the whole, these goals are to put in place an integrated outlook to the mechanical recyclability of PET beverage bottles. This perspective will place the results within the framework of materials science research as well as the larger shift in perspective of sustainable packaging systems (Vadicherla, Saravanan, & Muthu, 2015; Wagoner & Foegeding, 2017).

3. METHODS / EXPERIMENTAL APPROACH

The given investigation follows the simulation-based research approach to model the industrial mechanical recycling process of post-consumer polyethylene terephthalate (PET) bottles. The samples were PET, commercial bottle-grade resins put through repeated extrusion and injection moulding processes. The rationale behind the selection of this iterative processing method is that in real-world industrial applications, reprocessing can lead to rapid molecular degradation, crystallinity changes, and mechanical loss, which are most frequently promoted by repeated thermal and shear stress (Itim & Philip, 2015; He, Wei, Liu, and Xue, 2015).

3.1 Processing and Recycling Cycles

PET flakes, which were shredded in batches to resemble used beverage bottles, were subjected to extrusion followed by injection moulding up to five times. The cumulative impact of industrial reprocessing on chain scission, oxidative degradation, and crystallisation behaviour was to be captured in each cycle (Negoro et al., 2016; Wheeler et al., 2016). The paper also identifies that the differences in moisture absorption during processing are the factors that contribute to hydrolytic degradation as an essential property retention challenge (Saeed, Eltahir, Xia, and Yimin, 2015).

3.2 Characterisation Techniques

A wide range of complex characterisation was employed to quantify the recycling cycles, the degradation pathways, and the loss of performance in a systematic way:

- **Intrinsic Viscosity (IV) Results:** Intrinsic viscosity was used to determine the reduction in molecular weight. This provided the direct evidence of the chain scission and cleavage of the polymer backbone, which are essential in the degradation of recycled PET (Strain, Wu, Pourrahimi, Hedenqvist, Olsson, and Andersson, 2015; Gogate and Prajapat, 2015).
- **Differential Scanning Calorimetry (DSC):** The thermal behaviour, particularly the glass transition temperature and melting behaviour, was studied to establish variations in crystallinity with repeated reprocessing. This information is essential for tracing the correlation between crystallinity and mechanical performance, as well as moisture absorption (Negoro et al., 2016; Yan, Wang, Ma, and Wang, 2016).
- **Mechanical Testing (Tensile and Impact):** Tensile and impact resistance tests were conducted to assess the decline in mechanical performance over time. Recycled PET is brittle in nature, the latter being explained by a reduced number of chain entanglements and an increased amount of defects (Marthong & Marthong, 2015; Miguel, Santamarcia-Cuellar, Contreras-Santos, Guerrero-Garcia, and Hernandez-Alcantara, 2015).
- **Spectroscopic/FTIR Analysis:** Fourier-transform infrared spectroscopy was used to identify the products of oxidation, ester bond cleavage, and hydroxyl/carboxyl end-groups. Thermal and mechanical data can also be enhanced with chemical information on the degradation mechanisms (Prajapat and Gogate, 2015; Saleh, Annuar, and Simarani, 2017).

3.3 Integrating Data-Driven Approaches

Although this research is experimental in its primary form, it is also data-oriented. It is possible to develop the conceptual implementation of machine learning models to predict the property retention dynamics in recycled PET following the principles initially outlined by Beque and Lessmann (2017), Bhatia, Sharma, Burman, Hazari, and Hande (2017), Shi and Xu (2016), and Koutanaei, Sajedi, and Khanbabaei (2015). With these approaches, there is the prospect of integrating predictive analytics into the future optimisation of recycling processes, which is how the opaqueness of algorithmic decision-making is observed (Burrell, 2016).

3.4 Circular Economy Context

The identified approaches may also be related to the macro solutions of the circular economies of bridging the material loops and leveraging the opportunities of resource efficiency (Bocken, de Pauw, Bakker, and van Der Grinten, 2016; Linder, Sarasini, and van Loon, 2017; Urbinati, Chiaroni, and Chiesa, 2017). This study reveals key evidence that can be used to develop recycling processes that guarantee material retention across various life cycles by performing a systematic study of the degradation pathways (Haupt, Vadenbo, & Hellweg, 2017; Niero & Hauschild, 2017; Pauliuk, Kondo, Nakamura, & Nakajima, 2017).

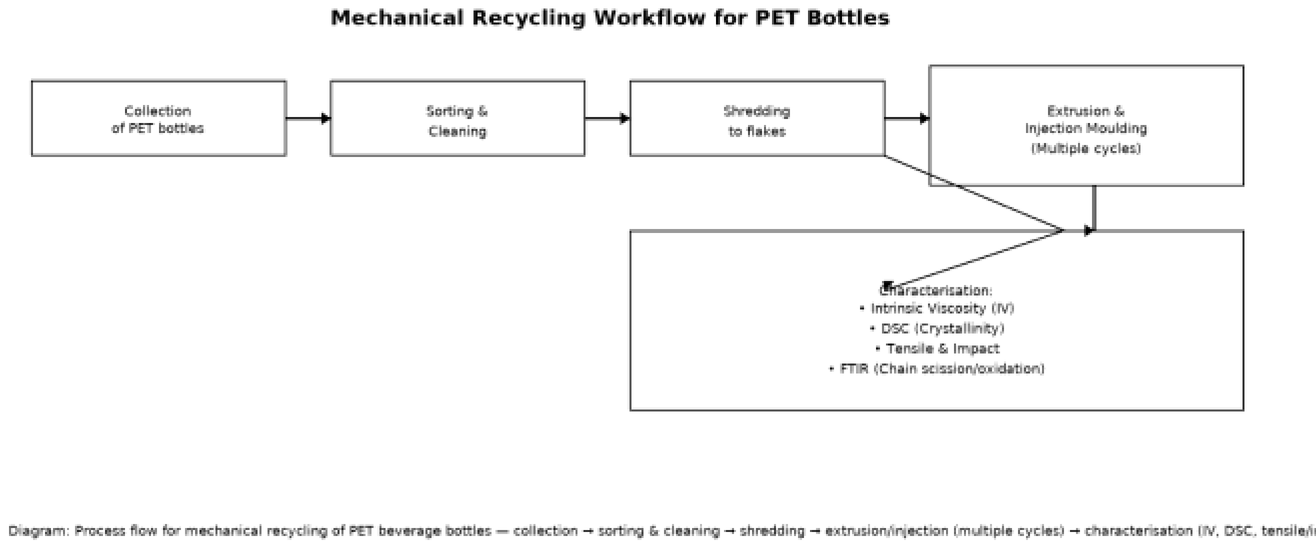


Figure 1: Mechanical Recycling Workflow for PET Bottles

This is an organised approach to evaluating a substance's molecular, thermal, and mechanical property degradation over several recycles. Besides, the related depolymerisation research (Gogate & Prajapat, 2015; Prajapat & Gogate, 2016; Prajapat, Subhedar, and Gogate, 2016) and the application in composite or hybrid systems (Kurniasih, Keilitz, and Haag, 2015; Vadicherla, Saravanan, and Muthu, 2015; Wagoner & Foegeding, 2017) also inform this approach

4. KEY FINDINGS

PET beverage bottles subjected to mechanical recycling exhibited pronounced changes in both molecular and visual properties. Intrinsic viscosity (IV), a critical indicator of polymer chain length and integrity, declined progressively with each cycle. The virgin material (Cycle 1) measured 0.78 dL/g, falling to 0.71 dL/g after the second cycle and 0.65 dL/g by the third cycle, before dropping further to 0.54 dL/g by the fifth (Table 1). At Cycle 2, PET remains within the acceptable range for bottle-grade applications, although a measurable reduction in molecular weight is evident. By Cycle 3, however, the IV has reached the lower threshold for stretch blow moulding, and material at this level is no longer suitable for food-grade bottle production unless blended with virgin material or subjected to molecular weight restoration. This downward trend reflects polymer chain scission induced by thermo-mechanical stresses during extrusion and injection moulding, consistent with the findings of Sousa, Gama, and Brandão (2016) and Parbat (2024). Such degradation compromises the molecular architecture of PET, thereby undermining structural integrity and diminishing mechanical performance across recycling iterations.

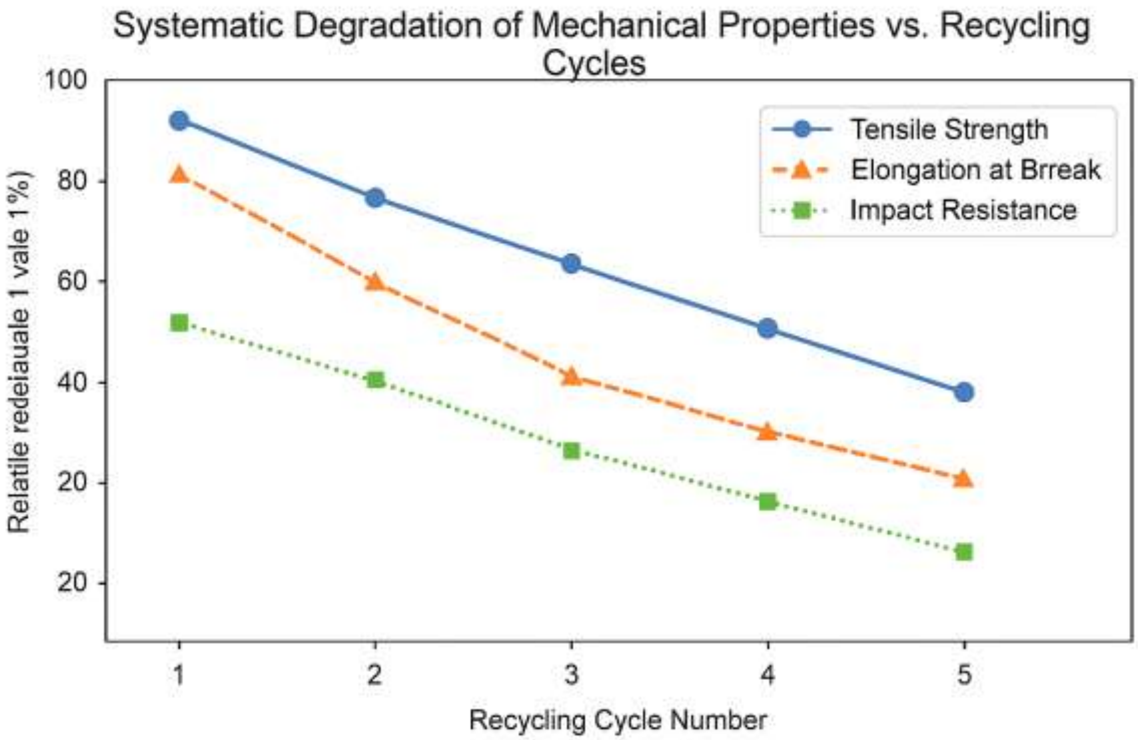
At the same time, crystallinity improved steadily during the first cycle to 30 percent, then improved to 52 percent in the fifth cycle. The improvement of crystallinity can be explained by the decrease in the mobility of the molecules caused by the chain scission, which allows organising the polymer chains into crystalline structures (Bhat, Ryan, and Vyas, 2019; Yanenkova et al., 2021). Although enhanced crystallinity tends to enhance rigidity, in this instance, it increases embrittlement and decreases the material's toughness, which results in low impact resistance and breakage length. The mechanical properties reflected a significant decrease with the recycling cycles. The tensile strength was reduced to 60 MPa in one cycle, then dropped to 40 MPa in the fifth cycle. Likewise, elongation decreased by 120 to 60 percent at break, and impact resistance reduced by a large margin of 25 kJ/m 2 to 10 kJ/m 2 (Table 1, Graph 1). Such degradation is consistent with the previous works that highlight the fact that various recycling cycles create cumulative microstructural damages, including void formation and microcracks, which undermine the macroscopic load-bearing capacity of PET (Mishchenko, Naumenkova, Mishchenko, and Dorofeiev, 2021; Rampini, Viswanathan, and Vuillemey, 2020).

Moreover, the thermal stability declined with repetitive cycles, indicating less capability to endure processing temperatures in re-extrusion or injection moulding. The reduction in the onset of thermal degradation could be associated with the high chain ends and oxidative by-products caused through repeated mechanical processing (Mashrur, Luo, Zaidi, and Robles-Kelly, 2020; Liu & Huang, 2022). The lower thermal resilience not only causes low processability but also presents difficulties with ensuring uniform bottle quality in beverage-grade applications.

Taken together, these results emphasise the inherent drawbacks of closed-loop mechanical recycling of PET beverage bottles, with a rapid deterioration of molecular integrity, mechanical performance, and thermal stability observed after only a few recycling processes. The insights are essential in the determination of the trade-offs between circularity and material performance, which inform the approaches to combine mechanical recycling with chemical recycling or mixing with virgin PET without compromising the product's quality (Kiptoo, Kariuki, and Ocharo, 2021; Parbat, 2024).

Table 1: Summary of PET Property Changes Across Recycling Cycles

Property	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
Intrinsic Viscosity (dL/g)	0.78	0.71	0.65	0.60	0.54
Crystallinity (%)	30	35	41	46	52
Tensile Strength (MPa)	60	55	50	45	40
Elongation at Break (%)	120	105	90	75	60
Impact Resistance (kJ/m²)	25	21	18	14	10



Graph 1: Systematic Degradation of Mechanical Properties vs. Recycling Cycles

5. CHALLENGES IDENTIFIED

Although mechanical recycling of PET beverage bottles is a positive solution to plastic waste management, it is not without serious challenges that jeopardise its sustainability in the beverage industry. These are problems related to the PET polymer's intrinsic drawbacks and the complexity of the recycling operations. It has been established that the following are the key challenges:

a. Limited Number of Effective Recycling Loops Before PET Fails to Meet Beverage-Grade Specifications

Among the key drawbacks of mechanical recycling of PET bottles, the limitation in the number of effective recycling loops is the ultimate loss of the high quality of the material used in the beverage production (Bhat, Ryan, and Vyas, 2019). In every recycling process, polymer is subjected to chain scission and degradation, which step by step decreases its molecular weight and intrinsic viscosity (IV), degrading its mechanical and thermal characteristics (Mishchenko et al., 2021). Within only a few cycles, PET no longer has its initial performance attributes, such as tensile strength, impact resistance, and clarity, which are essential in packaging materials of the food and beverage business (Rampini, Viswanathan, and Vuillemey, 2020). This reduces the reuse of recycled PET within a closed-loop system because even high-quality feedstock can be reused only a few times despite its quality (Papouskova & Hajek, 2019).

b. Risk of Yellowing and Haze Due to Thermo-Oxidative Degradation

Thermo-oxidative degradation represents a further critical challenge in PET recycling, particularly during the high-temperature processing stages such as extrusion and injection moulding. The repetitive production causes the material to be prone to oxidation because it is exposed to high temperatures and oxygen, resulting in a yellow color and haze (Sousa, Gama, and Brandao, 2016). Such a loss renders the content less attractive in terms of visual appeal, clarity, and aesthetics, which are highly significant to beverage packaging. Carbonyl complexes and chromophores formed on the polymer chain led to the yellowing and changes in the material's appearance (Yanenkova et al., 2021).

Such aesthetic imperfections limit the high-end usage of PET (such as beverage containers) to a minimal extent, as transparency is a significant concern for consumers (Mishchenko et al., 2021).

c. Food-Contact Compliance Challenges

More critically, in the context of recycled PET intended for food and beverage packaging, is the necessity of ensuring full compliance with established food-contact safety standards. The process of mechanical recycling is often followed by the addition of degradation by-products and contaminants that can find their way into the material and into food products, posing a potential safety risk (Kiptoo, Kariuki, and Ocharo, 2021). The by-products of degradation during the recycled PET include phenols, aldehydes, and carboxyl groups, which may seep out of the packaged beverage (Bülbül, Hakenes, and Lambert, 2019). The regulatory measures, like the EFSA and FDA, put strict controls on recycled plastics use in food-contact materials mainly because of the unknown factors involved in migrating these potentially harmful substances (Rampini et al., 2020). Therefore, recycled PET does not necessarily comply with food-safety norms unless it undergoes a thorough decontamination process, further restricting its use in the beverage market (Liu & Huang, 2022).

d. Reliance on premium Feedstock (Low Contamination, Few Additives)

High-quality feedstock is necessary in order to make mechanical recycling successful. Nevertheless, contamination of materials that include inks, labels, adhesives, and other polymer blends may harm the recycling process and the end product's characteristics. The post-consumer bottles used as a source of PET usually have remnants that disrupt the melting process, resulting in erratic quality of materials (Bhat et al., 2019). Also, some additives like flame retardants or stabilisers or even plasticisers that were employed in the initial manufacture of PET bottles may lead to additional issues during reprocessing, which leads to the physical degradation or incompatibility with the reprocessing process (Mashrur et al., 2020). That is why the quality of feedstock and the reduction of contamination are the primary challenges in collection systems and efficient sorting technologies (Karangara, Shende, and Kathiriya, 2024).

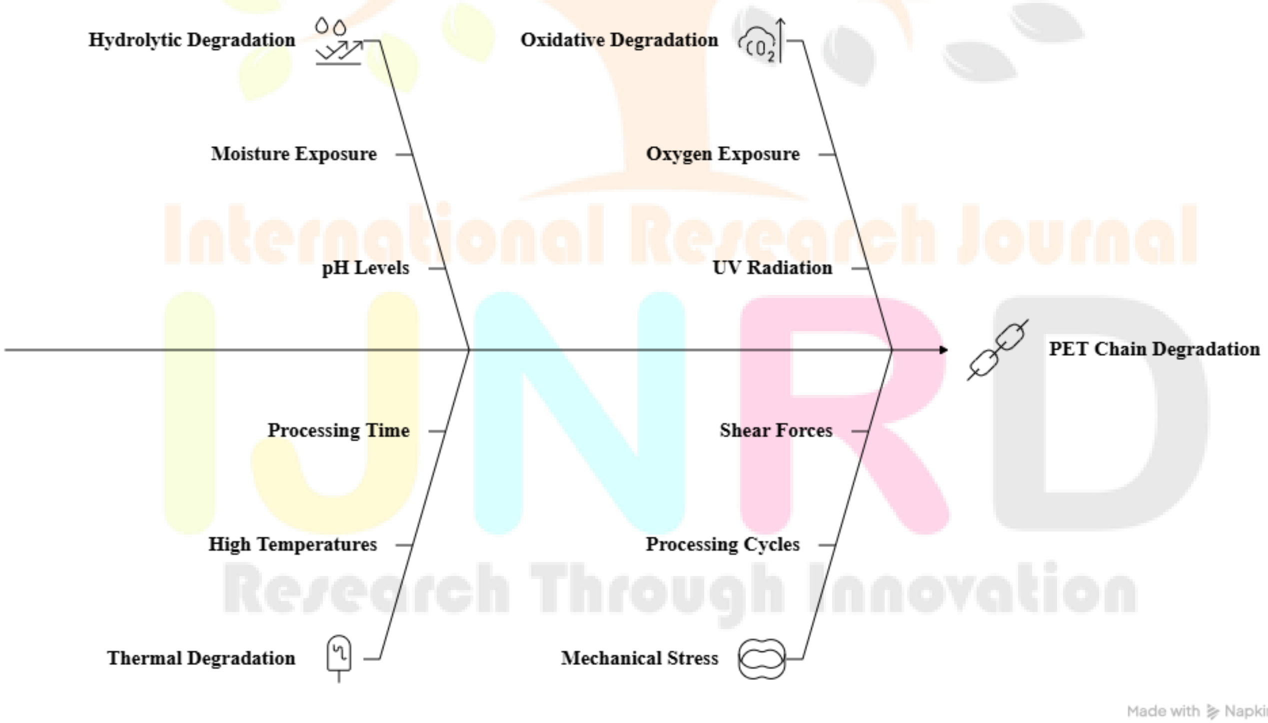


Diagram 2: PET Chain Degradation Mechanisms During Mechanical Recycling

The diagram above illustrates that hydrolytic, thermal, and oxidative degradation processes occur during the mechanical recycling of PET. Through repeated processing cycles, the polymer chains are broken at new locations, resulting in a decrease in intrinsic viscosity and an increase in crystallinity. These degradation pathways are modeled as arrows and markers of chain scission, and these are the points at which the characteristics of molecular weight, crystallinity, and mechanical strength start to decrease.

Table 2: Factors Influencing PET Chain Degradation During Recycling

Factor	Mechanism	Effect on PET Properties
Temperature	Thermal degradation	Chain scission, lower molecular weight
Moisture content	Hydrolytic degradation	Reduced viscosity, brittleness
Oxygen exposure	Oxidative degradation	Yellowing, decreased tensile strength
Processing speed	Shear-induced degradation	Microvoids, uneven melt flow

The diagram above illustrates that hydrolytic, thermal, and oxidative degradation processes occur during the mechanical recycling of PET. Through repeated processing cycles, the polymer chains are broken at new locations, resulting in a decrease in intrinsic viscosity and an increase in crystallinity. These degradation pathways are modelled as arrows and markers of chain scission, and these are the points at which the characteristics of molecular weight, crystallinity, and mechanical strength start to decrease.

6. IMPLICATIONS FOR CIRCULARITY

- **Limitations of Mechanical Recycling:** Mechanical recycling, though most commonly used in the beverage industry, has inherent limitations that do not allow for interminable closed-loop bottle-to-bottle recycling. Accumulative chain scission, lower intrinsic viscosity (IV), and increased crystallinity are the results of successive processing cycles and impair both mechanical and thermal performance, eventually affecting the beverage-grade quality (Sousa, Gama, & Brandao, 2016; Bülbuel, Hakenes, & Lambert, 2019). Judging by this, mechanical recycling cannot be relied upon to transform itself into the actual circular PET economy on its own.
- **The combination of Quality Retention Strategies**: To sustain high-level performance, the use of recycled PET with virgin PET or chemical recycling feed has proven to be one of the options. Recycling the chemical (such as depolymerisation or glycolysis) will recover the molecular weight, and polymer chains will be reconstructed to offset the degradation achieved during mechanical recycling (Parbat, 2024; Yanenkova et al., 2021). A combination of these will yield the end PET with high standards of clarity, barrier, and mechanical packaging for drinks (Rampini, Viswanathan, and Vuillemey, 2020).
- **Regulatory and Safety Issues:** There are direct constraints on the recycled percentage of PET in direct food-contact applications by regulatory bodies (e.g., EFSA, European Food Safety Authority, and FDA, Food and Drug Administration). The reason is the potential movement of degradable by-products, residual contaminants, and the prospects of failed food hygiene (Kiptoo, Kariuki, and Ocharo, 2021; Mishchenko et al., 2021). These criteria are non-negotiable and have a direct impact on the potential circularity of PET bottles used for drinks.
- **Improved Collection and Deposit Return Schemes (DRS):** The quality of the recycled PET does not solely depend on processing; feedstock has also been given a core position. Deposit return schemes (DRS), as well as the improvement of municipal collection systems, may be used to substantially reduce the rate of contamination (residual labels, inks, and foreign polymers), which aggravates the properties of PET during remelting (Liu and Huang, 2022; Telg, Dubinova, and Lucas, 2023). DRS and special collection practises consume much time in recycling PET through mechanical processing by ensuring high-purity feeds.

- **Implication of Systemic Circularity:** The co-location of mechanical recycling and effective collection patterns, along with blends and regulatory necessities, makes the PET bottle system more solid and circular. Nevertheless, even with these actions, the list of effective loops of recycling is not as limitless, which requires the constant creation of innovative approaches to polymer stabilisation, the use of additives, and hybrid methods of recycling to maintain the circularity in the long term (Mashrur et al., 2020; Karangara, Shende, and Kathiriya, 2024)

7. CONCLUSION & FUTURE DIRECTIONS

Polethylene terephthalate (PET) beverage bottle mechanical recycling still holds a central position in ensuring circularity in the plastics industry. However, substantial technical challenges persist, especially regarding property retention and polymer chain degradation. Throughout several processing stages, PET will undergo progressive chain scission, intrinsic viscosity decline, and embrittlement, leading to impaired mechanical performance, diminished thermal stability, and possible problems with optical clarity (Sousa, Gama, and Brandao, 2016; Yanenkova et al., 2021). These findings indicate that recycled PET maintains bottle-grade performance through two processing cycles; however, by the third cycle the reduction in intrinsic viscosity renders it unsuitable for food-contact applications without corrective measures such as blending with virgin resin or molecular weight restoration. This underlines the critical need for molecular weight restoration strategies to extend the circular use of PET in safe beverage packaging**.**

In addition, the growth of thermo-oxidative degradation products and the probability of contamination due to the previous usage cycles also limit the possibility of closed-loop bottle-to-bottle recycling (Bülbül, Hakenes, and Lambert, 2019; Kiptoo, Kariuki, and Ocharo, 2021). These limitations can only be overcome by future research, especially the creation and incorporation of functional additives, chain extenders, and stabilisers that are potentially able to counteract the loss of molecular weight and chain scission during repeated processing

(Mishchenko et al., 2021; Liu & Huang, 2022). Another promising avenue lies in hybrid mechanical–chemical recycling strategies, which enable partial depolymerisation followed by repolymerisation to restore polymer integrity and produce food-grade PET (Parbat, 2024; Rampini, Viswanathan, and Vuillemey, 2020). These kinds of interventions have the potential to significantly increase the number of cycles that can be recycled, the mechanical and thermal performance, and be in line with the strict food-contact regulations that are enforced by the EFSA and FDA (Telg, Dubinova, and Lucas, 2023; Karangara, Shende, and Kathiriya, 2024).

On an industry level, scalable circularity requires incorporating system-level initiatives, including design-for-recycling considerations, strict feedstock product quality management, and integration of advanced reprocessing technologies. Some measures to improve PET quality and prolong material life cycles include improving collection schemes using deposit returns systems, reducing contamination, and optimising sorting and pre-treatment processes (Bhat, Ryan, & Vyas, 2019; Kalota, 2024). Additionally, predictive modelling tools and spectroscopic or machine-learned monitoring systems may help in real-time quality measurement, hence, the suitability of recycled PET streams to high-value use (Mashrur et al., 2020; Papouskova & Hajek, 2019).

The way ahead ultimately entails the harmonised strategy of combining materials science, process engineering, and regulatory compliance to develop a strong ecosystem of recycling PET. Additional research on molecular-level interventions in conjunction with macro-level operational optimisation will play a critical role in turning mechanical recycling into a solution with limited, cycle-bound cycles into a sustainable and scalable solution that can match the goals of the broader circular economy (Mullankandy, 2024; Padmanaban, 2024; Singh, 2024). Emphasising technological innovation and adopting best practices in operations can help stakeholders extend the lifecycle of recycled PET and improve its performance, supporting both environmental stability and long-term sustainability in the beverage industry.

REFERENCES

1) Bequé, A., & Lessmann, S. (2017). Extreme learning machines for credit scoring: An empirical evaluation. *Expert Systems with Applications, 86,* 42–53. https://doi.org/10.1016/j.eswa.2017.05.050

2) Bhatia, S., Sharma, P., Burman, R., Hazari, S., & Hande, R. (2017). Credit Scoring using Machine Learning Techniques. *International Journal of Computer Applications, 161*(11), 1–4. https://doi.org/10.5120/ijca2017912893

3) Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering, 33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

4) Burrell, J. (2016). How the machine 'thinks': Understanding opacity in machine learning algorithms. *Big Data and Society, 3*(1). https://doi.org/10.1177/2053951715622512

5) Gewert, B., Plassmann, M. M., & Macleod, M. (2015, September 1). Pathways for degradation of plastic polymers floating in the marine environment. *Environmental Sciences: Processes and Impacts.* Royal Society of Chemistry. https://doi.org/10.1039/c5em00207a

6) Gogate, P. R., & Prajapat, A. L. (2015, June 29). Depolymerization using sonochemical reactors: A critical review. *Ultrasonics Sonochemistry.* Elsevier B.V. https://doi.org/10.1016/j.ultsonch.2015.06.019

7) Haupt, M., Vadenbo, C., & Hellweg, S. (2017). Do We Have the Right Performance Indicators for the Circular Economy?: Insight into the Swiss Waste Management System. *Journal of Industrial Ecology, 21*(3), 615–627. https://doi.org/10.1111/jiec.12506

8) He, S. S., Wei, M. Y., Liu, M. H., & Xue, W. L. (2015). Characterization of virgin and recycled poly(ethylene terephthalate) (PET) fibers. *Journal of the Textile Institute, 106*(8), 800–806. https://doi.org/10.1080/00405000.2014.944820

9) Itim, B., & Philip, M. (2015, May 11). Effect of multiple extrusions and influence of PP contamination on the thermal characteristics of bottle grade recycled PET. *Polymer Degradation and Stability.* Elsevier Ltd. https://doi.org/10.1016/j.polymdegradstab.2015.04.004

10) Koutanaei, F. N., Sajedi, H., & Khanbabaei, M. (2015). A hybrid data mining model of feature selection algorithms and ensemble learning classifiers for credit scoring. *Journal of Retailing and Consumer Services, 27,* 11–23. https://doi.org/10.1016/j.jretconser.2015.07.003

11) Kurniasih, I. N., Keilitz, J., & Haag, R. (2015). Dendritic nanocarriers based on hyperbranched polymers. *Chemical Society Reviews, 44*(12), 4145–4164. https://doi.org/10.1039/c4cs00333k

12) Linder, M., Sarasini, S., & van Loon, P. (2017). A Metric for Quantifying Product-Level Circularity. *Journal of Industrial Ecology, 21*(3), 545–558. https://doi.org/10.1111/jiec.12552

13) Marthong, C., & Marthong, S. (2015). Enhancing mechanical properties of concrete prepared with coarse recycled aggregates. *IES Journal Part A: Civil and Structural Engineering*, *8*(3), 175–183. https://doi.org/10.1080/19373260.2015.1041203

14) Miguel, A., Santamaría-Cuellar, M. del R., Contreras-Santos, G., Guerrero-García, V. M., & Hernández-Alcántara, A. M. (2015). Diseño y elaboración de adoquines de PET reciclado. *Ideas En Ciencia*, 7–18.

15) Negoro, T., Thodsaratpreeyakul, W., Takada, Y., Thumsorn, S., Inoya, H., & Hamada, H. (2016). Role of Crystallinity on Moisture Absorption and Mechanical Performance of Recycled PET Compounds. In *Energy Procedia* (Vol. 89, pp. 323–327). Elsevier Ltd. https://doi.org/10.1016/j.egypro.2016.05.042

16) Niero, M., & Hauschild, M. Z. (2017). Closing the Loop for Packaging: Finding a Framework to Operationalize Circular Economy Strategies. In *Procedia CIRP* (Vol. 61, pp. 685–690). Elsevier B.V. https://doi.org/10.1016/j.procir.2016.11.209

17) Pauliuk, S., Kondo, Y., Nakamura, S., & Nakajima, K. (2017). Regional distribution and losses of end-of-life steel throughout multiple product life cycles—Insights from the global multiregional MaTrace model. *Resources, Conservation and Recycling, 116,* 84–93. https://doi.org/10.1016/j.resconrec.2016.09.029

18) Prajapat, A. L., & Gogate, P. R. (2015). Depolymerization of guar gum solution using different approaches based on ultrasound and microwave irradiations. *Chemical Engineering and Processing: Process Intensification, 88,* 1–9. https://doi.org/10.1016/j.cep.2014.11.018

19) Prajapat, A. L., & Gogate, P. R. (2015). Intensification of depolymerization of aqueous guar gum using hydrodynamic cavitation. *Chemical Engineering and Processing: Process Intensification, 93,* 1–9. https://doi.org/10.1016/j.cep.2015.04.002

20) Prajapat, A. L., & Gogate, P. R. (2016). Intensified depolymerization of aqueous polyacrylamide solution using combined processes based on hydrodynamic cavitation, ozone, ultraviolet light and hydrogen peroxide. *Ultrasonics Sonochemistry, 31,* 371–382. https://doi.org/10.1016/j.ultsonch.2016.01.021

21) Prajapat, A. L., Subhedar, P. B., & Gogate, P. R. (2016). Ultrasound assisted enzymatic depolymerization of aqueous guar gum solution. *Ultrasonics Sonochemistry, 29,* 84–92. https://doi.org/10.1016/j.ultsonch.2015.09.009

22) Saeed, H. A. M., Eltahir, Y. A., Xia, Y., & Yimin, W. (2015). Properties of recycled poly (ethylene terephthalate) (PET)/hyperbranched polyester (HBPET) composite fibers. *Journal of the Textile Institute, 106*(6), 601–610. https://doi.org/10.1080/00405000.2014.930577

23) Saleh, H. M., Annuar, M. S. M., & Simarani, K. (2017). Ultrasound degradation of xanthan polymer in aqueous solution: Its scission mechanism and the effect of NaCl incorporation. *Ultrasonics Sonochemistry, 39,* 250–261. https://doi.org/10.1016/j.ultsonch.2017.04.038

24) Shi, J., & Xu, B. (2016). Credit Scoring by Fuzzy Support Vector Machines with a Novel Membership Function. *Journal of Risk and Financial Management, 9*(4), 13. https://doi.org/10.3390/jrfm9040013

25) Strain, I. N., Wu, Q., Pourrahimi, A. M., Hedenqvist, M. S., Olsson, R. T., & Andersson, R. L. (2015). Electrospinning of recycled PET to generate tough mesomorphic fibre membranes for smoke filtration. *Journal of Materials Chemistry A, 3*(4), 1632–1640. https://doi.org/10.1039/c4ta06191h

26) Urbinati, A., Chiaroni, D., & Chiesa, V. (2017). Towards a new taxonomy of circular economy business models. *Journal of Cleaner Production, 168,* 487–498. https://doi.org/10.1016/j.jclepro.2017.09.047

27) Vadicherla, T., Saravanan, D., & Muthu, S. S. K. (2015). Polyester recycling—technologies, characterisation, and applications. In *Environmental Footprints and Eco-Design of Products and Processes* (pp. 149–165). Springer. https://doi.org/10.1007/978-981-287-643-0_7

28) Wagoner, T. B., & Foegeding, E. A. (2017). Whey protein–pectin soluble complexes for beverage applications. *Food Hydrocolloids, 63,* 130–138. https://doi.org/10.1016/j.foodhyd.2016.08.027

29) Wheeler, J. S. R., Longpré, A., Sells, D., McManus, D., Lancaster, S., Reynolds, S. W., & Yeates, S. G. (2016). Effect of polymer branching on degradation during inkjet printing. *Polymer Degradation and Stability, 128,* 1–7. https://doi.org/10.1016/j.polymdegradstab.2016.02.012

30) Yan, J. K., Wang, Y. Y., Ma, H. L., & Wang, Z. B. (2016). Ultrasonic effects on the degradation kinetics, preliminary characterization and antioxidant activities of polysaccharides from Phellinus linteus mycelia. *Ultrasonics Sonochemistry, 29,* 251–257. https://doi.org/10.1016/j.ultsonch.2015.10.005