Advances in Recycling Strategies for Multilayer Food Packaging – Current Approaches to Address Non-Recyclable Packaging Systems

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Abstract

Multilayer plastic packaging accounts for approximately 13% of total plastic packaging and about 28% of flexible plastic packaging worldwide. It combines distinct polymer layers to achieve superior barrier performance, mechanical stability, and extended shelf life. However, the deliberate material heterogeneity that enables functional advantages simultaneously creates substantial end-of-life challenges. Multilayer structures are largely incompatible with conventional mechanical recycling systems and are therefore frequently directed to incineration or downcycling pathways, undermining circular economy objectives.

This study analyses current technological approaches to recycling multilayer food packaging and evaluates their environmental, technical, and economic limitations. A systematic literature review is combined with expert-informed scenario analysis to examine secondary (mechanical), thermochemical (pyrolysis-based), and solvent-based chemical recycling strategies. The analysis highlights structural constraints of mechanical recycling, including polymer immiscibility, contamination, and quality degradation. Thermochemical conversion enables feedstock recovery but is limited by high energy demand, contaminant variability, and the need for multi-stage upgrading processes. Solvent-based separation technologies such as the STRAP process demonstrate potential for high-purity polymer recovery; however, solvent regeneration, impurity accumulation, and scale-up complexity significantly affect environmental performance.

The findings reveal a structural gap between ambitious regulatory targets, particularly under the EU Packaging and Packaging Waste Regulation, and the technological maturity of existing recycling infrastructures. No single pathway currently provides a comprehensive solution. Instead, a hybrid recycling landscape integrating mechanical, thermochemical, and solvent-based approaches appears most realistic in the near term.

The study concludes that achieving circularity for multilayer food packaging requires systemic alignment across material design, advanced separation technologies, purification strategies, economic incentives, and regulatory frameworks.

1 Introduction

This study is guided by the central research question of whether multilayer food packaging, despite its deliberate material heterogeneity, can be reconciled with the principles of a circular economy under current technological and regulatory conditions. The analysis proceeds from the hypothesis that no single recycling pathway is capable of delivering closed-loop circularity for multilayer systems at industrial scale. Instead, it is assumed that structural material incompatibility, contaminant variability, and process-related energy demands impose systemic limitations that cannot be overcome by incremental optimization within one technological domain alone. A second hypothesis proposes that emerging regulatory frameworks, particularly within the European Union, are accelerating innovation but simultaneously exposing a structural gap between policy ambition and technological maturity.

To test these assumptions, the study systematically evaluates mechanical, thermochemical, solvent-based, and chemical delamination approaches with regard to technical feasibility, environmental performance, economic viability, and scalability. By combining a structured literature review with scenario-based analysis, the article seeks to assess whether hybrid technological configurations, rather than singular solutions, represent the most plausible pathway toward circular integration of multilayer food packaging.

Multilayer plastic packaging differs fundamentally from mono-material systems due to its composite architecture. Distinct layers of polymers, adhesives, aluminium, paper, and functional coatings are combined to achieve tailored performance characteristics. Individual layers may provide oxygen barrier resistance, moisture protection, mechanical strength, flexibility, or thermal stability, thereby enabling extended shelf life and enhanced product protection, particularly in food and pharmaceutical applications (Anwar et al. 2024). Manufacturing processes such as co-extrusion and lamination allow the precise integration of these functionalities; however, they also increase structural complexity and production costs compared to single-polymer packaging solutions.

Multilayer food packaging typically consists of four to seven functional layers, each designed to fulfil a specific performance requirement. A representative multilayer food packaging structure described in experimental research consists of three polymer layers separated by adhesives and aluminium, with a total thickness of approximately 60 µm (Šleiniūtė et al. 2024). In this structure, the outer polymer layer provides mechanical protection and printability, intermediate layers include adhesive and aluminium components contributing to barrier functionality, and the innermost layer ensures food contact compliance.

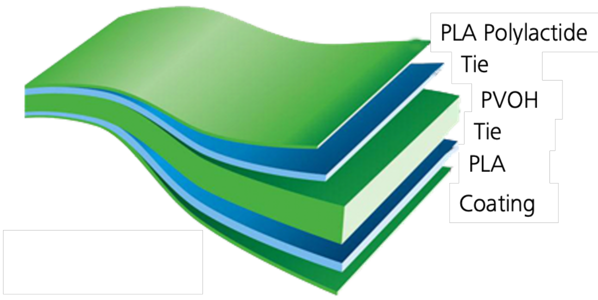

Fig. 1: Multilayer film for Cheese or fresh pasta packaging with six layers (Food and Drink Business News 2021)

Common barrier materials such as ethylene vinyl alcohol (EVOH), polyamide (PA), metallized PET, or aluminium foil provide oxygen and aroma resistance, while polyethylene (PE) and polypropylene (PP) layers ensure sealability and moisture protection. These engineered combinations significantly extend product shelf life and reduce food waste.

The environmental challenge emerges primarily at the end-of-life stage. Although multilayer structures are resource-efficient during use and can reduce food waste due to their superior barrier properties, their heterogeneous composition complicates identification, sorting, and material separation within existing waste management systems. Consequently, multilayer packaging waste is frequently classified as mixed plastic waste and is commonly directed to incineration with energy recovery rather than material recycling (Anwar et al. 2024). This practice conflicts with circular economy principles and perpetuates dependence on virgin fossil-based feedstocks.

At the same time, global plastic production continues to increase, with packaging representing a substantial share of overall polymer demand. Despite political initiatives in Europe aiming for all plastic packaging to be reusable or recyclable by 2030, recycling rates for complex multilayer materials remain comparatively low (Anwar et al. 2024). The structural incompatibility between multilayer design and conventional mechanical recycling infrastructure has therefore emerged as one of the most significant barriers to circular plastics management.

In response to these challenges, the development of improved and more widely applicable recycling methods, including secondary (mechanical) and tertiary (chemical) recycling, has gained considerable momentum. This trend has been further accelerated by the European Union's recently adopted Packaging and Packaging Waste Regulation (PPWR, Regulation (EU) 2025/40), which represents a landmark shift in legislative efforts to embed circular economy principles into packaging systems across all Member States. Entering into force in early 2025 and becoming applicable from August 2026, the regulation introduces harmonised recyclability criteria, mandatory design-for-recycling assessments, minimum recycled content targets for plastics, and strengthened extended producer responsibility schemes. Its overarching objective is that all packaging placed on the EU market must be recyclable by 2030 and recycled at scale by 2035. These requirements directly influence material selection, product design, and end-of-life management strategies, significantly increasing the relevance of advanced recycling technologies, particularly for multilayer flexible packaging (Bokor 2025).

The urgency of this issue is underscored by recent research. Nazemi (2025: 1–25), in the study "Toward a Sustainable Circular Economy of Multilayer Plastic Packaging" published in the Journal of Circular Economy and Sustainability, reports that multilayer plastic packaging accounts for approximately 13% of total plastic packaging and about 28% of flexible plastic packaging worldwide. Despite this substantial share, flexible multilayer materials remain difficult to recycle using established mechanical technologies due to their multi-polymer and composite structure.

Against this background, the PPWR's stringent design and recyclability obligations are intensifying research and innovation efforts in both mechanical and chemical recycling pathways. Advancing these technologies is essential to ensure regulatory compliance and to enable the transition toward a genuinely circular packaging economy within the European Union.

This paper therefore analyses the currently available recycling options for multilayer plastic packaging, evaluates their potential, and critically examines their present technological and economic limitations.

2 Methodology

The methodological framework of this study integrates a systematic literature review with expert-based scenario planning in order to examine potential future developments in multilayer plastic waste management. The results indicate a significant increase in academic attention to multilayer plastic waste management since 2017, with particularly strong research contributions from industrialized countries such as the United States, Italy, Japan, and Finland (Anwar et al., 2024).

The geographic distribution of publications reveals clear disparities in technological infrastructure, funding capacity, and regulatory pressure across regions. Industrialised nations tend to emphasise advanced chemical recycling technologies and design-for-recycling strategies, whereas emerging economies frequently encounter infrastructural limitations that contribute to higher rates of landfilling or uncontrolled disposal. Although circular economy principles are widely recognised at the global level, their practical implementation differs substantially depending on socioeconomic and regulatory conditions (Anwar et al., 2024). Keyword network analyses further demonstrate that recycling technologies, life cycle assessment, sustainability metrics, and extended producer responsibility form closely interconnected thematic clusters. This interconnection highlights the systemic relationship between technological innovation, regulatory frameworks, and market mechanisms.

Building on these insights, a scenario planning framework was developed to explore possible future pathways. The findings of the literature review provided the conceptual basis for identifying key variables that may influence the development of multilayer plastic waste management systems. In a subsequent step, relevant influencing factors were compiled and systematically categorised, with particular emphasis on available technological options and current challenges.

3. Results & Discussion – A Scenario Analysis

Most synthetic polymers used as functional layers in multilayer composite packaging, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyamide (PA), ethylene vinyl alcohol (EVOH), ethylene vinyl acetate (EVA), polyurethane (PUR), and polylactic acid (PLA), are derived primarily from fossil-based hydrocarbons. With the exception of certain bio-based materials such as PLA, the vast majority of these conventional polymers are not biodegradable. They do not readily decompose under natural environmental conditions and can persist for decades or even centuries. As a result, plastic materials accumulate in landfills and increasingly in terrestrial, freshwater, and marine ecosystems.

The scale of this accumulation is substantial. Current estimates suggest that approximately 30 million tonnes of plastic waste have accumulated in seas and oceans, while an additional 109 million tonnes are present in rivers (Jansen 2023: 54-64). As Bremer (2022) observes, the continued accumulation of plastics in river systems indicates that leakage into marine environments will persist for decades, even if the generation of mismanaged plastic waste is significantly reduced.

This trend is reinforced by growing global production and consumption levels. According to the OECD (2022), global plastic waste generation has doubled over the past two decades. A considerable proportion of this waste is either landfilled, incinerated (thereby contributing to CO_2 emissions) or released into the environment due to insufficient waste management infrastructure. Globally, only around 9% of plastic waste is recycled (2022). Beyond marine pollution, increasing evidence documents contamination of freshwater systems and terrestrial ecosystems. The persistence of plastic waste is therefore particularly problematic given its near-permanent nature and the presence of synthetic polymers, chemical additives (such as plasticizers and stabilizers), fillers, flame retardants, and synthetic fibres.

A closer look at production structures highlights the dominance of a limited number of polymer groups. Geyer, Jambeck, and Law (2017) report that plasticizers, fillers, and flame retardants account for approximately three quarters of all plastic additives. In terms of non-fibre plastic production volumes, polyethylene represents about 36%, polypropylene 21%, and polyvinyl chloride (PVC) 12%, followed by polyethylene terephthalate (PET), polyurethane (PUR), polystyrene (PS), and polyamide (PA), each accounting for less than 10%. Together, these seven polymer groups are estimated to comprise approximately 92% of all plastics ever produced (2017).

These figures illustrate not only the dominance of a limited range of fossil-based polymers but also the structural importance of packaging as the primary application sector. Consequently, improving the recyclability and circular integration of packaging materials, particularly complex multilayer systems, remains a central lever for reducing global plastic waste accumulation.

Given that packaging represents the largest application sector for non-fibre plastics and that multilayer materials further complicate material recovery, improving recycling performance is not merely desirable but essential for mitigating environmental accumulation and reducing dependence on virgin feedstocks. Against this background, this chapter examines current technological foundations, potentials, and limitations of secondary (mechanical) and tertiary (thermochemical and chemical) recycling pathways as key strategies for reintegrating plastic waste, particularly multilayer packaging, into a circular material economy.

3.1 Mechanical Recycling and Compatibilization

Mechanical recycling remains the predominant approach in Europe and involves shredding, washing, extrusion, and pelletizing mixed plastic waste streams (Anwar et al. 2024). Within the plastics industry, in mechanical recycling, a distinction is made between primary and secondary recycling. Primary recycling refers to the closed-loop recovery of pre-consumer plastic scrap, which is reprocessed through mechanical or physical methods and reintroduced into the original production cycle with minimal loss of material quality. In contrast, secondary recycling involves the processing of post-consumer or post-commercial plastic waste and is typically associated with material downgrading. This form of recycling also relies on mechanical and physical reprocessing techniques; however, the resulting products generally exhibit reduced quality compared to primary recyclates. The decline in material performance is largely attributable to contamination and degradation of packaging materials during use and collection (Jansen 2023: 54-64).

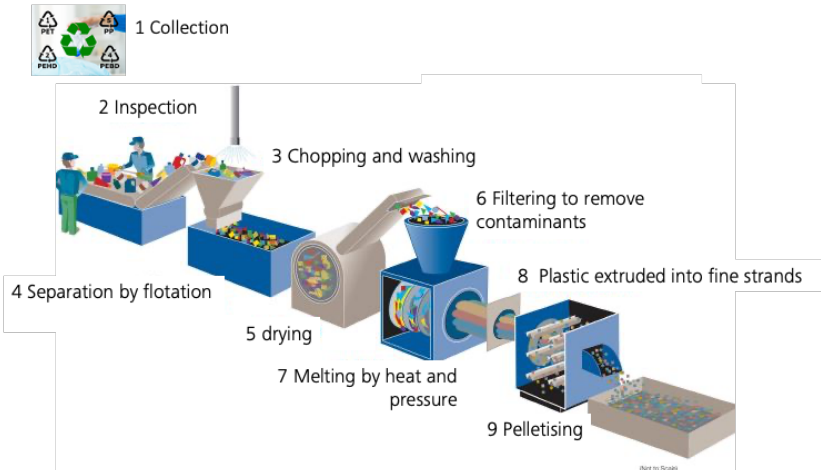

Fig: 2: The steps of mechanical plastic recycling (Alberta Plastics Recycling Association 2025)

Secondary recycling of multilayer packaging is constrained by a combination of material heterogeneity, limited sortability, and quality losses during melt processing. Because multilayer structures deliberately combine immiscible polymers and functional interlayers (for example sealants, barrier layers and tie layers), they rarely behave as a single, stable melt stream. As a result, conventional reprocessing tends to produce blends with unstable properties, which undermines "like-for-like" (closed-loop) recycling and pushes outputs toward downcycled applications (Kaiser, Schmid and Schlummer 2018: 2; Seier et al., 2022: 1).

The immiscibility of different polymers within multilayer structures leads to poor phase separation, interfacial adhesion, and downgraded mechanical properties in recycled materials. Even if the film material is of single origin, for instance, polyethylene, the recycling of film and flexible packaging still presents specific challenges and difficulties. According to Enrico Siewert (2022) 'the first challenge is the low bulk density of these materials […]. [Plastic films and foils] tend to move around on a sorting plant's conveyors and wrap themselves around the bearings of the shafts, affecting the equipment's performance and maintenance. Also, these materials are susceptible to trapping moisture, they tend to crumple locking in the moisture, and it takes a lot of energy to clean them'.

A second, closely related challenge is that mechanical recycling generally presupposes reasonably pure polymer fractions, whereas multilayer formats are difficult to separate at scale and therefore remain mixed or enter the wrong sorting fractions. This means multilayers either have to be removed as contaminants or they dilute the quality of otherwise recyclable streams, reinforcing low-value outlets (Kaiser, Schmid and Schlummer 2018: 2; Seier et al. 2022: 1). Even if compatibilisers can improve interfacial adhesion in some blends, the underlying multilayer design still embeds polymers with very different processing windows; in modified-atmosphere packaging, for instance, PET-driven processing temperatures can exceed those of polyolefins and thereby accelerate degradation phenomena that reduce toughness and ductility (Seier et al. 2022: 6–7).

Finally, contamination and embedded non-target materials can strongly degrade recyclate quality in practice. Post-consumer multilayer packaging often includes organics, labels, inks, adhesives and non-PET components, and these impurities can survive washing and persist into extrusion, where they contribute to chain scission, discoloration/yellowing, and reductions in intrinsic viscosity and molecular mass. Empirical recycling trials on PET multilayer trays show clear deterioration trends with increasing impurity content and explicitly point to feedstock purification as a key lever for improving rPET quality (Santomasi et al., 2024: 2–3, 14–6).

Therefore, flexible plastic packaging and multi-material multilayer plastic packaging (MMPP) exhibit particularly low recycling rates, primarily due to inadequate sorting technologies and the high proportion of multilayer materials whose individual layers cannot be easily separated. Compatibilisation strategies have been developed to address this challenge by adding chemical agents that improve bonding between otherwise incompatible polymers. However, while these approaches can stabilise mixed polymer streams, they typically lead to downcycled products rather than enabling true closed-loop material recovery.

Economic feasibility analyses indicate that profitability depends strongly on polymer type, yield, and secondary market prices, and many recycling fractions exhibit negative net present values without policy support (Anwar et al. 2024). This economic constraint further limits large-scale mechanical recycling of multilayer waste.

3.2 Thermochemical Recycling (Pyrolysis)

Thermochemical conversion technologies capable of processing complex plastic waste streams include gasification, pyrolysis, fluid catalytic cracking, and hydrocracking (Ragaert et al., 2017). Among these approaches, pyrolysis has emerged as a particularly promising option for plastic waste that is difficult to depolymerise using conventional methods, such as MMPP (Thiounn and Smith, 2020).

There are two basic variants: direct pyrolysis and indirect pyrolysis. In direct pyrolysis, the material to be pyrolysed is heated by combustion gases. The required thermal energy can be generated from the pyrolysis feedstock itself. In this case, the reaction temperature is controlled by regulating the air supply into a closed container. It is conducted at elevated temperatures under oxygen-free conditions (anaerobic conditions), during which polymer chains undergo thermal degradation. With subsequent upgrading steps, the resulting products can be refined into petrochemical feedstocks such as naphtha or diesel-range hydrocarbons (Ragaert et al., 2017).

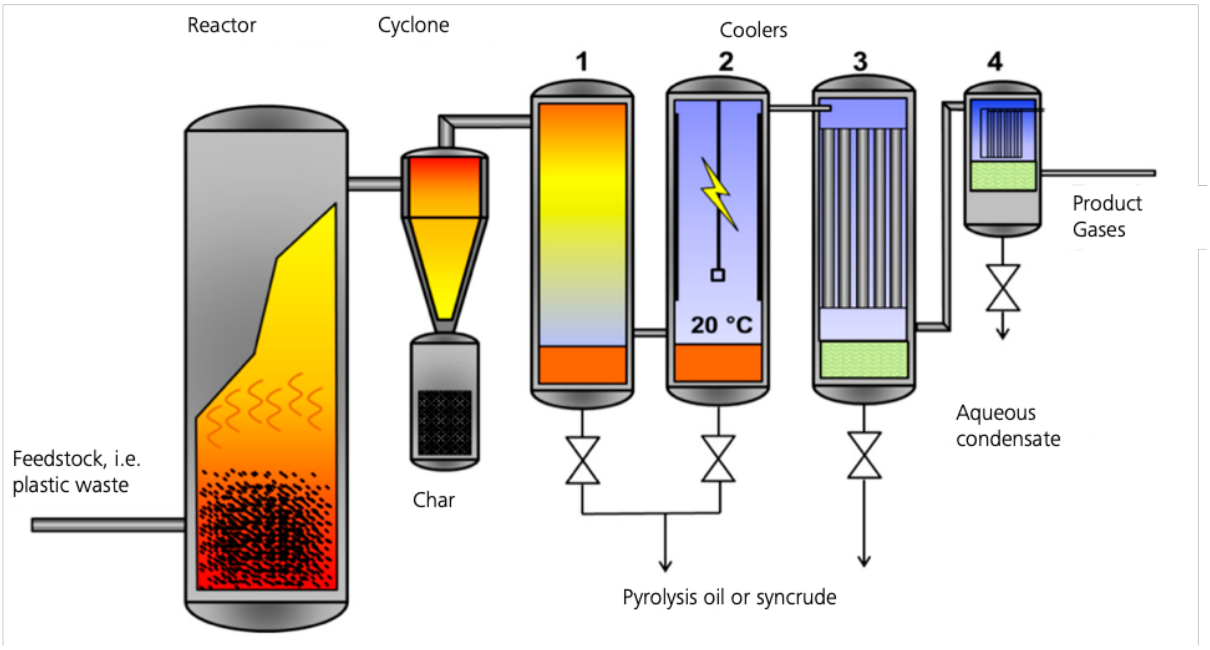

Fig.: 3 A general layout of the pyrolysis process including reactor, cyclone, and condensation stages (Pandey et al. 2019: 2533)

The pyrolysis process begins with the introduction of the feedstock, such as plastic waste i.e. MMPP, into a closed reactor vessel, commonly referred to as the pyrolysis reactor. From this point, the mode of heat transfer determines whether the system operates as direct or indirect pyrolysis.

In direct pyrolysis the feedstock is heated through direct contact with hot combustion gases. A controlled amount of air or oxygen is introduced into the reactor, allowing partial combustion of either a fraction of the feedstock or an auxiliary fuel. This limited oxygen supply generates high-temperature gases inside the reactor, which in turn provide the thermal energy required to initiate and sustain pyrolytic decomposition. The reaction temperature, typically ranging between approximately 350 and 800 °C depending on the material and the targeted product distribution, is regulated by adjusting the air input. Increasing the oxygen supply enhances combustion and raises the temperature, whereas reducing it favours predominantly pyrolytic conditions with limited oxidation.

In contrast, indirect pyrolysis involves heating the reactor externally, usually by means of hot gases circulating in a furnace or heating jacket. Because heat is transferred through the reactor wall rather than through direct contact with combustion gases, a strictly oxygen-free atmosphere can be maintained within the reactor chamber. This configuration prevents combustion and ensures controlled thermal degradation under anaerobic conditions.

Under oxygen-limited or oxygen-free conditions, the long-chain organic polymers thermally decompose into smaller molecular fragments. The process typically produces three main product fractions: non-condensable gases, condensable vapours that can be cooled to form pyrolysis oil, and a solid carbon-rich residue known as char. The volatile products exit the reactor and are usually passed through a cyclone separator to remove entrained solid particles. The cleaned vapour stream then enters a condensation system, where liquid fractions are recovered. The remaining non-condensable gases may be recirculated to supply process heat or treated prior to discharge. The solid char residue remains in the reactor and is removed via a dedicated discharge system.

In more advanced configurations, catalysts may be employed to influence reaction pathways and selectively tailor the production of gaseous, liquid, or wax fractions. In certain cases, dehydrogenating or dehydrating agents are added to modify product composition. These thermochemical approaches extend beyond the capabilities of mechanical recycling by enabling the recovery of molecular building blocks from heterogeneous and contaminated plastic waste streams (Garcia and Robertson, 2017).

Thermochemical conversion technologies such as pyrolysis are increasingly discussed as potential solutions for the treatment of complex plastic waste streams. However, these processes remain energy-intensive, and their overall life-cycle greenhouse gas performance is highly dependent on process efficiency, reactor design, and the carbon intensity of the energy source used. Beyond energy considerations, a central challenge concerns the variability in the quality of the resulting pyrolysis oil, often referred to as syncrude. The composition and purity of this oil are strongly influenced by the characteristics of the input stream, including the degree of contamination, the polymer composition, and the presence of composite materials. Since post-consumer plastic waste varies significantly in quality, origin, and material composition, the resulting syncrude exhibits corresponding fluctuations in chemical composition and performance properties. Besides fluctuations in quality of the syncrude a major issue is high levels of contaminants which pose considerable technical challenges and imply high costs for purification:

Kusenberg et al. (2022), in their *study Opportunities and challenges for the application of post-consumer plastic waste pyrolysis oils in steam crackers*, demonstrate that pyrolysis oils derived from real waste streams contain substantially higher and more diverse levels of contaminants than conventional fossil-based feedstocks. The authors identify nitrogen-, oxygen-, and chlorine-containing compounds, as well as trace metals, as particularly problematic. These contaminants can lead to corrosion, fouling, and catalyst poisoning in downstream upgrading processes and petrochemical units. Kusenberg et al. (2022) therefore frame contaminant variability as a fundamental barrier to the direct “drop-in” substitution of fossil feedstocks with waste-derived pyrolysis oils and emphasise the need for advanced feedstock characterisation, purification technologies, and standardised quality specifications.

Similarly, Ragaert et al. (2022), in their study *Towards high-quality petrochemical feedstocks from mixed plastic waste pyrolysis oils*, highlight that critical contaminants such as nitrogen, oxygen, halogens, and metals are directly linked to feedstock origin. These substances often originate from heteroatom-containing polymers, additives, stabilisers, printing inks, and organic or inorganic residues present in post-consumer waste. The authors demonstrate that such contaminants reduce the chemical stability and upgrading potential of pyrolysis oils, thereby limiting their suitability for reuse as high-quality petrochemical feedstocks.

A broader and more practice-oriented perspective is provided by Chang (2023) in the review article *Plastic waste as pyrolysis feedstock for plastic oil production*. This study synthesises evidence from multiple experimental and industrial cases and underscores how real-world feedstock variability directly influences product composition, process stability, and upgrading requirements. Chang (2023) concludes that inconsistent waste quality and contamination levels remain major constraints for the production of a consistent and refinery-compatible syncrude.

In addition, Genuino et al. (2022), in their investigation *Pyrolysis of mixed plastic waste (DKR-350),* identify chlorine as a particularly critical contaminant in mixed plastic streams. Chlorine-containing polymers, especially polyvinyl chloride (PVC), can generate hydrochloric acid and chlorinated organic compounds during pyrolysis. These compounds pose significant technical challenges, including corrosion risks and the need for extensive gas cleaning and oil purification steps. The presence of chlorine therefore, represents a key limitation for the large-scale utilisation of MMPP waste-derived syncrude in existing petrochemical infrastructures.

However, Pyrolysis-derived syncrude can be purified and upgraded through a combination of physical and catalytic post-treatment steps. Vacuum distillation has been shown to effectively fractionate post-consumer plastic pyrolysis oil into defined boiling ranges while substantially reducing metal contaminants. Zeb et al. (2023: 5–9) report that distillation can remove the majority of trace metals and improve fuel-range characteristics; however, they also emphasise that heteroatom species such as chlorine, nitrogen, and oxygen are only partially removed through this step. Consequently, distillation alone is generally insufficient to meet petrochemical or steam cracker specifications.

To address specific contaminant classes, adsorption-based purification strategies have been investigated. Romero et al. (2024: 6–10) demonstrate that Na-zeolite systems can significantly reduce chlorine concentrations in plastic waste pyrolysis oils under relatively mild operating conditions. Their results show substantial de-chlorination performance with regenerable adsorbents, highlighting adsorption as a technically viable pre-treatment step to mitigate corrosion risks and downstream processing constraints. Nevertheless, adsorption is typically selective for particular contaminants and does not comprehensively upgrade the oil.

More extensive upgrading can be achieved through catalytic hydrotreating. Yoon et al. (2024: 4-8) show that hydrotreating over sulfided NiMo/Al_2O_3 catalysts effectively removes heteroatoms such as nitrogen and chlorine while simultaneously hydrogenating olefinic compounds, thereby improving thermal stability and compatibility with refinery infrastructure. Their findings indicate that refinery-style hydrogenation can substantially enhance syncrude quality, bringing it closer to conventional fossil-derived feedstocks. However, this approach requires hydrogen supply, high-pressure operation, and refinery-type infrastructure, which increases capital and operational complexity.

Overall, the literature indicates that purification of pyrolysis syncrude is technically feasible but generally requires a multi-step upgrading train. Distillation improves fractionation and reduces metals, adsorption targets specific contaminants such as chlorine, and hydrotreating enables deeper heteroatom removal and stabilization. The key message is that no single unit operation is sufficient to achieve petrochemical-grade quality; rather, integrated purification strategies are necessary to compensate for feedstock variability and contaminant complexity.

3.3 Chemical Recycling (Solvent-Targeted Recovery and Precipitation)

An alternative to the limitations of mechanical and thermochemical recycling is provided by solvent-based separation technologies, which represent an advanced category within chemical recycling. One of the most prominent examples is the Solvent-Targeted Recovery and Precipitation (STRAP) process. This approach selectively dissolves individual polymer layers from multilayer materials based on thermodynamic principles, thereby enabling the recovery of high-purity polymers without chemically degrading the polymer chains (Anwar et al., 2024). The principal objective of such processes is to preserve polymer chain integrity, avoid depolymerization, and facilitate closed-loop recycling for complex multilayer packaging structures.

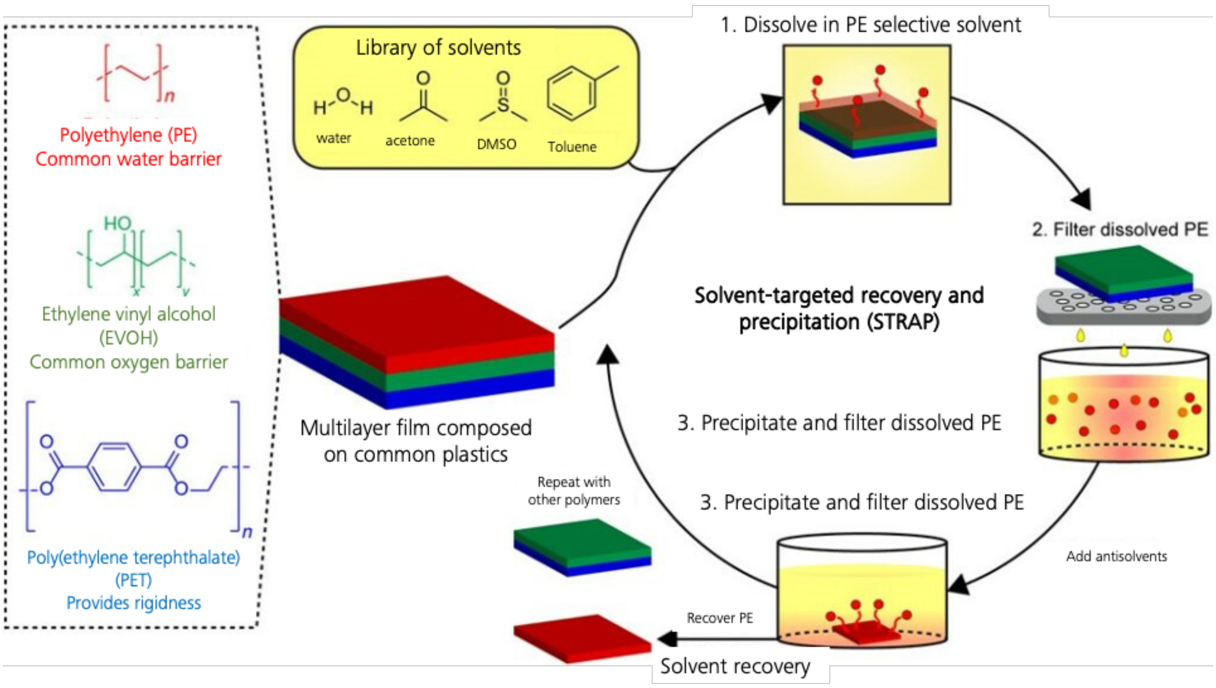

Fig.4: Three basic stages of the Solvent-Targeted Recovery and Precipitation (STRAP) process (Walker et al. 2020).

Despite these advantages, solvent-based technologies are characterised by considerable physicochemical complexity and significant scale-up challenges. The processes require controlled dissolution, filtration, precipitation, and solvent regeneration steps, all of which must be firmly integrated. Solvent loops must be continuously purified to remove contaminants that accumulate during repeated processing cycles, and maintaining high polymer and solvent yields under continuous, high-throughput industrial conditions remains difficult. As Zhou et al. (2025: 27(3),1124–46) note, “disadvantages of these solvent-based technologies are their physicochemical complexity and the difficulty in scaling up to achieve continuous operations with high polymer and solvent yields and throughputs.”

A recurring finding in the literature is that solvent recovery, rather than polymer dissolution itself, often dominates overall energy demand and environmental burden. Life-cycle assessments of STRAP variants demonstrate that distillation and solvent regeneration steps are major contributors to process energy consumption. Depending on the source of heat and the efficiency of solvent recovery, these stages can significantly diminish the anticipated climate benefits of the technology. Furthermore, such assessments reveal that environmental impacts may shift toward increased toxicity and water use, as solvent handling, purification, and regeneration become central components of the system design (Munguía-López et al., 2025: 1611–25).

A second major concern relates to the use of antisolvents and multi-step precipitation. Solvent-based separation typically involves repeated cycles of selective dissolution followed by precipitation, either through the addition of antisolvents or via temperature-induced phase separation. These additional unit operations increase equipment requirements, separation effort, and operational complexity. The overall performance of the process becomes highly sensitive to solvent recovery efficiency and to the purity and stability of the recovered polymer across multiple cycles (Li et al. 2024: 148–60).

Third, real MMPP streams introduce impurities that accumulate within solvent loops and necessitate further purification steps. Even when selective dissolution is technically feasible, non-polymeric components such as printing inks, adhesives, coatings, fillers, and low-molecular-weight fractions may partition into the solvent phase and build up over time. Recent studies by Yan et. Al (2024), Ügdüler et al. (2025), and Van Melkebeke et al. (2024) on flexible packaging separation of MMPP indicate that such impurity accumulation can require additional solvent cleaning steps or the introduction of secondary solvents. This increases both cost and environmental impact, thereby undermining the concept of a straightforward closed-loop solvent system (Li et al. 2024).

A fourth limitation concerns occupational, environmental, and regulatory constraints associated with solvent use. Reviews of multilayer separation technologies highlight volatile organic compound (VOC) emissions, solvent toxicity in certain systems, and the environmental burdens of solvent purification, particularly via energy-intensive distillation, as significant barriers to industrial implementation. These constraints have motivated research into alternative solvent systems, including switchable hydrophilicity solvents, deep eutectic solvents, and bio-derived media, which aim to reduce environmental and health impacts (Li et al. 2024: 1670).

Finally, scale-up and continuous high-throughput operation remain unresolved challenges for many solvent-based concepts. Although laboratory and pilot-scale demonstrations, including STRAP, have shown high material recovery efficiencies under controlled conditions, peer-reviewed analyses emphasise that translating these processes to industrial-scale, continuous operation is complex. Solvent loops, filtration or centrifugation steps, precipitation units, and solvent regeneration systems must operate in a tightly integrated and feedstock-tolerant manner. Variability in waste composition further complicates stable operation at scale (Shen et al. 2022: 24(5), 1934–52).

In summary, while solvent-based separation technologies offer significant potential for high-purity polymer recovery and closed-loop recycling of MMPP, solvent recovery requirements, energy demand, impurity management, regulatory constraints, and scale-up challenges remain critical issues that require further technical and systemic optimisation.

3.4 Nitric Acid-Assisted Delamination and Polymer Recovery

Recent experimental investigations by Šleiniūtė et al. (2024) into nitric acid-assisted delamination provide insight into alternative separation strategies for MMPP. In controlled laboratory experiments, multilayer snack packaging was treated with diluted nitric acid combined with ultrasonic agitation to dissolve aluminum layers and weaken adhesive bonds. The process achieved polymer recovery rates exceeding 93% of the initial mass, demonstrating technical feasibility for selective separation (2024).

Mechanical characterisation of recovered polymers revealed differentiated behaviour among layers.[1] The findings demonstrate that chemical delamination can preserve essential mechanical properties of recovered polymers, supporting potential reuse in secondary applications. However, the dissolution and subsequent polymer precipitation stages require energy-intensive solvent recovery or evaporation steps, which contribute to CO_2-equivalent emissions (Šleiniūtė et al. 2024). Thus, while nitric acid-assisted delamination represents a promising technical route, its environmental performance depends on process optimisation and emission mitigation.

In particular, nitric-acid-assisted delamination is technically promising for aluminium-containing multilayer structures, but several limitations constrain its environmental performance, scalability, and safe industrial deployment. Despite its technical feasibility, nitric acid-assisted delamination faces several important limitations related to environmental performance, process control, and systemic implementation.

A first limitation concerns process safety and emission control. Acid-based delamination methods can generate nitrogen oxide (NO_x) emissions during reaction and require dedicated gas scrubbing and containment systems to ensure occupational and environmental safety. Li et al. (2024: 5–6) emphasise that acid-based delamination strategies, including nitric acid systems, raise concerns regarding solvent/acid handling, corrosivity, and gaseous emissions, which increase technical complexity and regulatory requirements for industrial implementation. The corrosive nature of nitric acid further necessitates acid-resistant reactor materials and increases capital and maintenance costs (Li et al. 2024: 6).

A second limitation relates to energy demand and process sensitivity. Experimental investigations into nitric-acid delamination demonstrate that separation efficiency depends strongly on parameters such as acid concentration, temperature, ultrasonic intensity, and treatment duration (Šleiniūtė 2023: 4–6). The study shows that higher delamination rates require intensified operating conditions, which implies greater energy input for heating and ultrasonication. More generally, kinetic and environmental assessments of acid-based delamination processes indicate that increased reaction efficiency is often associated with higher thermal energy consumption, thereby shifting the environmental burden toward energy-related CO_2 emissions (Ügdüler et al. 2022: 7–9). As Ügdüler et al. (2022: 10) conclude, the carbon footprint of chemical delamination is highly sensitive to process energy sources and solvent recovery efficiency.

A third limitation concerns system integration and feedstock variability. While laboratory-scale studies demonstrate high recovery efficiencies under controlled conditions, real post-consumer multilayer waste streams exhibit significant heterogeneity in adhesive composition, ink systems, contamination levels, and polymer thicknesses. Kaiser, Schmid and Schlummer (2018: 2–4) note that MMPP recycling solutions are constrained by upstream collection and sorting performance, and that chemical separation routes require sufficiently pure and pre-treated feedstock to operate effectively. Without reliable front-end sorting and

[1] Polymer 1 exhibited tensile strengths averaging approximately 5 MPa under certain conditions, whereas polymer 2 displayed significantly lower fracture strengths around 0.09 MPa, reflecting its elastomeric characteristics (Šleiniūtė et al. 2024). Polymer 3 showed intermediate mechanical performance with fracture strength values between 1.79 and 3.19 MPa depending on treatment conditions (2024).

preprocessing, acid-based delamination may face operational instability and increased chemical consumption.

Taken together, these limitations indicate that nitric acid-assisted delamination, although technically promising, requires careful evaluation within a broader techno-economic and environmental systems framework. Emission control, energy intensity, corrosion management, solvent/acid recovery, and feedstock preparation represent critical barriers that must be addressed before large-scale industrial deployment can be considered viable.

3.5 Circular Economy Integration and Policy Drivers

The transition from a linear "take–make–dispose" model toward a circular plastics economy requires coordinated innovation across design, infrastructure, and governance. Extended Producer Responsibility (EPR) schemes are increasingly emphasised as instruments to shift lifecycle responsibility to manufacturers and incentivise design-for-recycling strategies (Anwar et al. 2024). Packaging guidelines now promote reduced material complexity, elimination of incompatible layers, and compatibility with existing sorting technologies.

Life cycle assessment studies indicate that packaging weight reduction may sometimes yield greater environmental benefits than improvements in recyclability, particularly in applications such as meat packaging where the environmental burden of the packaged product exceeds that of the packaging itself (Anwar et al. 2024). This highlights the importance of holistic system evaluation rather than isolated recyclability metrics.

Energy recovery remains part of the circular economy debate. While it does not preserve material value, it provides an outlet for highly contaminated or technically unrecyclable streams. Nevertheless, reliance on energy recovery cannot substitute for systemic material circularity.

5. Conclusion

This paper has examined the technological, environmental, and regulatory dimensions of recycling strategies for MMPP, highlighting the structural tension between functional performance and end-of-life recoverability. Multilayer systems provide essential barrier properties, lightweight construction, and mechanical stability that significantly reduce food waste and improve resource efficiency (Anwar et al. 2024; Nazemi 2025). However, their deliberately engineered material heterogeneity fundamentally conflicts with conventional recycling infrastructures and remains one of the most persistent barriers to circular plastics management (Kaiser, Schmid and Schlummer 2018).

The analysis demonstrates that no single recycling pathway currently provides a comprehensive solution. Mechanical recycling remains the dominant route in Europe but is constrained by polymer immiscibility, contamination, and thermal degradation, often resulting in downcycling rather than closed-loop recovery (Seier et al., 2022; Santomasi et al., 2024). Thermochemical technologies such as pyrolysis expand the range of treatable waste streams and enable feedstock recovery; however, they face challenges related to energy demand, contaminant variability, and complex upgrading requirements (Kusenberg et al. 2022; Ragaert, Delva and Van Geem 2022; Chang 2023). The need for multi-stage purification, such as distillation, adsorption, and hydrotreating, further illustrates the technical and economic constraints of producing refinery-compatible syncrude from post-consumer waste (Zeb et al. 2023; Romero et al. 2024; Yoon et al. 2024).

Solvent-based chemical recycling approaches, including the Solvent-Targeted Recovery and Precipitation (STRAP) process, demonstrate strong potential for high-purity polymer recovery while preserving polymer chain integrity (Walker et al. 2020). Nevertheless, life-cycle assessments indicate that solvent regeneration and distillation stages dominate energy demand and environmental impact, while impurity accumulation in solvent loops and scale-up challenges remain critical barriers (Shen et al. 2022; Munguía-López et al. 2023; Zhou et al. 2025). Recent research further confirms that dissolved pigments, adhesives, and additives require additional purification steps, increasing system complexity (Yan et al. 2025; Van Melkebeke et al. 2024; Ügdüler et al. 2025).

Experimental findings on nitric-acid-assisted delamination show that selective separation with polymer recovery rates exceeding 90% is technically feasible and that essential mechanical properties can be preserved (Šleiniūtė et al. 2024). However, the environmental viability of such approaches depends on managing energy consumption, solvent recovery efficiency, and process emissions.

A central finding of this study is the existence of a structural gap between ambitious circular economy targets, particularly under the European Packaging and Packaging Waste Regulation (Bokor 2025), and the current technological and economic maturity of available recycling systems. While extended producer responsibility schemes and design-for-recycling criteria are accelerating innovation (Anwar et al. 2024), industrial-scale solutions capable of consistently processing heterogeneous multilayer waste streams remain under development.

In the near term, a hybrid recycling landscape appears most realistic. Mechanical, thermochemical, and solvent-based technologies are likely to coexist, with regional adoption shaped by regulatory pressure, infrastructure capacity, and economic incentives. Ultimately, transitioning multilayer food packaging from a linear disposal challenge to a circular material resource requires systemic alignment across the entire value chain. Material innovation, advanced separation technologies, robust purification systems, economic instruments, and coherent regulatory enforcement must evolve in parallel. Only through coordinated technological and policy integration can the functional advantages of multilayer packaging be reconciled with genuine material circularity.

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