TECHNICAL WHITEPAPER

# Engineering Feedstocks for Chemical Recycling

*How feedstock purification determines pyrolysis oil quality, steam cracker acceptance and PPWR recycled-content compliance*

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# Contents

# Executive Summary

**AT A GLANCE**

- **The regulatory driver:** PPWR introduces mandatory recycled-content targets for food-grade plastic packaging by 2030, creating significant demand for high-quality post-consumer recycled polyolefins.
- **The gap mechanical recycling cannot close:** approximately 60% of post-consumer flexible packaging is coloured or heavily printed and cannot follow the mechanical route already demonstrated for natural and lightly coloured material.
- **The fixed constraint:** pyrolysis redistributes the elements already present in the feedstock — it does not remove them. Oil quality is therefore determined before the reactor, not within it.
- **The commercial opportunity:** a highly purified polyolefin feedstock can lift steam cracker substitution from around 1–2% to 30–40% — a step change, not an incremental gain, in recycled hydrocarbon demand.
- **The enabling technologies:** BOSS density separation and HydroDyn hydrodynamic cleaning address the two distinct contamination mechanisms — unwanted polymers and surface-entrapped residues — that stand between mixed waste and a naphtha-grade feedstock.

## Abstract

The Packaging and Packaging Waste Regulation (PPWR) introduces mandatory recycled-content targets for plastic packaging, creating a significant demand for food-grade recycled polyolefins by 2030. Previous work has demonstrated that natural and lightly coloured post-consumer flexible polyethylene can potentially be returned to food-contact applications through novel mechanical recycling technologies operating under Regulation (EU) 2022/1616. However, these materials represent only a minority of the household flexible packaging stream. Approximately 60% of post-consumer flexible packaging consists of coloured or heavily printed materials that cannot readily follow the same mechanical recycling route. Consequently, achieving future recycled-content targets will require mechanical and chemical recycling to operate as complementary technologies.

The objective of chemical recycling is to convert post-consumer polyolefins into a hydrocarbon feedstock capable of replacing fossil-derived naphtha within existing steam crackers, enabling the manufacture of new virgin-quality polymers. Pyrolysis is fundamentally a thermal cracking process that redistributes the elements already present within the feedstock. As a result, the chemistry of the pyrolysis oil is determined principally by the chemistry of the incoming material.

Modern flexible packaging is no longer composed solely of polyethylene. It is a complex engineered structure containing multilayer barrier polymers, nitrocellulose printing systems, paper labels, cellulose fibres, pressure-sensitive adhesives and numerous functional coatings. These materials introduce oxygen and nitrogen into the feedstock, where they are subsequently transferred into the pyrolysis products, reducing their similarity to conventional fossil-derived naphtha and limiting their utilisation within existing steam crackers.

This paper examines the principal sources of oxygen- and nitrogen-containing contamination in post-consumer flexible plastic packaging and explains how these contaminants influence pyrolysis oil quality and downstream steam cracker acceptance. It is proposed that feedstock purification represents one of the greatest opportunities for increasing recycled hydrocarbon utilisation, enabling substantially higher substitution of fossil-derived naphtha while supporting the recycled-content objectives established under PPWR.

# 1. Introduction

The transition towards a circular plastics economy is being driven by increasingly demanding regulatory requirements and growing commitments by brand owners to incorporate recycled content into plastic packaging. In Europe, the Packaging and Packaging Waste Regulation (PPWR) introduces mandatory recycled-content targets across a range of plastic packaging formats, including food-contact applications. Achieving these targets will require a significant increase in the availability of high-quality post-consumer recycled (PCR) polyolefins capable of replacing virgin materials within demanding packaging applications.

Previous work by the authors has proposed a novel mechanical recycling pathway for producing food-grade recycled polyethylene from post-consumer flexible packaging under the Novel Recycling Technology framework established by Regulation (EU) 2022/1616. That work demonstrated that carefully controlled feedstock preparation, purification and decontamination can provide a credible route for returning natural and lightly coloured post-consumer flexible polyethylene into food-contact applications.

However, these materials represent only a proportion of the household flexible packaging waste stream. Approximately 60% of post-consumer flexible plastic packaging consists of coloured, printed or otherwise contaminated materials that cannot readily be returned to food-contact applications through conventional mechanical recycling. If the recycled-content objectives established by PPWR are to be achieved, an alternative route is required for this substantial fraction of the waste stream.

**SCALE OF THE CHALLENGE**

**~60%**

of post-consumer flexible plastic packaging is coloured, printed or otherwise contaminated — and cannot follow the mechanical recycling route.

Chemical recycling, and in particular pyrolysis, offers the potential to convert post-consumer polyolefins into hydrocarbon feedstocks capable of replacing fossil-derived naphtha within existing petrochemical steam crackers. In doing so, coloured and heavily printed flexible packaging that cannot readily be mechanically recycled may once again become a source of virgin-quality polyethylene and polypropylene.

Despite considerable industrial interest in chemical recycling, the quality of pyrolysis oils remains one of the principal barriers to widespread adoption within existing petrochemical infrastructure. This is particularly important because the commercial objective of chemical recycling is not simply to generate a liquid hydrocarbon product, but to manufacture a feedstock whose composition closely resembles conventional fossil-derived naphtha and can therefore be incorporated into existing steam crackers at commercially meaningful substitution rates.

The chemistry of the resulting pyrolysis oil is fundamentally determined by the chemistry of the feedstock entering the reactor. Modern flexible packaging is no longer composed solely of polyethylene, but is instead a highly engineered composite containing multilayer barrier polymers, nitrocellulose printing systems, paper labels, cellulose fibres, pressure-sensitive adhesives and numerous functional coatings. These materials introduce oxygen and nitrogen into the feedstock which are subsequently redistributed throughout the pyrolysis products, reducing their suitability as direct substitutes for conventional naphtha.

This paper examines the principal sources of oxygen- and nitrogen-containing contamination within post-consumer flexible plastic packaging and explains how these contaminants influence pyrolysis oil quality and downstream steam cracker acceptance. It is proposed that feedstock purification, rather than simply maximising liquid yield, represents one of the greatest opportunities for increasing recycled hydrocarbon utilisation and supporting the recycled-content objectives established under PPWR.

> *Mechanical recycling and chemical recycling should not be viewed as competing technologies, but as complementary pathways designed to recover maximum value from different fractions of the same post-consumer flexible packaging stream.*

# 2. Evolution of Flexible Plastic Packaging

Flexible polyethylene packaging has become one of the most widely used packaging materials worldwide due to its low cost, excellent processability, seal-ability and moisture barrier performance. It is used extensively for food packaging, carrier bags, mailing bags, agricultural films and numerous consumer packaging applications.

From a recycling perspective, polyethylene appears to be an ideal material. It consists almost entirely of carbon and hydrogen and, when uncontaminated, provides an excellent feedstock for both mechanical and chemical recycling. However, modern flexible packaging is no longer manufactured from polyethylene alone.

Packaging designers have continually modified polyethylene structures to improve product protection, increase shelf life, enhance appearance and improve manufacturing performance. As a result, today's flexible packaging has evolved into a highly engineered composite containing multiple polymers, printing systems, labels, adhesives and functional coatings.

This evolution has been driven by the technical limitations of polyethylene itself.

Low-density polyethylene (LDPE) provides excellent resistance to moisture transmission and outstanding heat-sealing performance. However, its highly branched molecular structure produces relatively low crystallinity compared with high-density polyethylene (HDPE). The resulting amorphous regions allow oxygen, carbon dioxide and volatile organic compounds to diffuse more readily through the polymer, making LDPE a relatively poor gas barrier for many food packaging applications.

To overcome these limitations, additional materials have progressively been incorporated into flexible packaging structures.

Multilayer barrier polymers such as polyethylene terephthalate (PET), polyamide (PA) and ethylene vinyl alcohol (EVOH) were introduced to improve oxygen barrier performance, stiffness, puncture resistance and mechanical strength. At the same time, sophisticated printing systems employing nitrocellulose binders were developed to deliver high-quality graphics and rapid printing speeds. Paper labels, pressure-sensitive adhesives, barrier coatings and numerous functional additives were also incorporated to improve product presentation, consumer information, traceability and manufacturing efficiency.

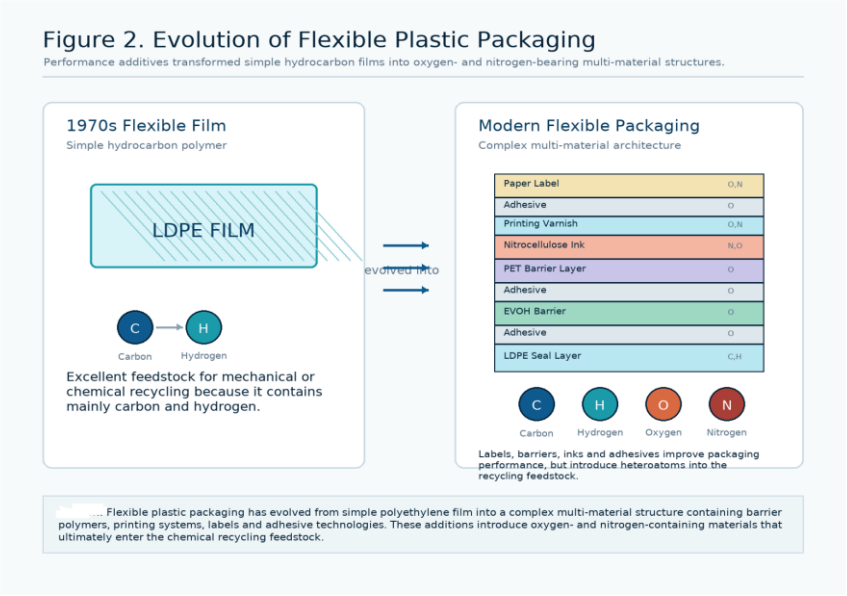


*Figure 1. Multilayer Barrier Film Structure — original artwork*

| ORIGINAL DIAGRAM DESCRIPTION | REDESIGNED DIAGRAM CONCEPT |
|---|---|

| | |
|---|---|
| A cross-sectional schematic of a multilayer flexible film, showing individual polymer layers (PE, PET/PA/EVOH barrier, adhesive tie layers) stacked and labelled with generic layer names. | Rebuild as a clean exploded-layer diagram in the brand palette: navy layer outlines on a pale-grey background, with each layer colour-coded by its elemental contribution — carbon/hydrogen layers in accent blue, oxygen-contributing layers in a warm amber, nitrogen-contributing layers in a muted red. Add small periodic-table-style element tags (C, H, O, N) beside each layer and a thin annotated call-out line naming each material, so the chemistry — not just the structure — is legible at a glance. |

Each of these developments successfully addressed a specific packaging requirement. Collectively, however, they transformed a relatively simple polyethylene film into a complex composite material containing a wide range of oxygen- and nitrogen-containing components.

From the perspective of the packaging industry, these developments have been highly successful. They have enabled lighter packaging, longer product shelf life, improved food protection and enhanced consumer appeal. From the perspective of chemical recycling, however, they present a fundamentally different challenge.

Pyrolysis does not distinguish between the functional purpose of individual packaging components. Every polymer, coating, label, adhesive and printing system entering the reactor contributes its elemental chemistry to the resulting pyrolysis products. Consequently, materials originally introduced to improve packaging performance become sources of contamination within the chemical recycling feedstock. Pyrolysis does not remove oxygen and nitrogen — it simply redistributes them.

Understanding the origin and function of these materials is therefore essential to understanding the chemistry of the resulting pyrolysis oil. The following sections examine the principal sources of oxygen- and nitrogen-containing contamination within modern flexible packaging and their impact on the production of hydrocarbon feedstocks suitable for steam cracking.

# 3. Pyrolysis — Converting Polyethylene into a Naphtha Substitute

The objective of chemical recycling is not simply to convert plastic waste into a liquid hydrocarbon. The objective is to manufacture a recycled feedstock capable of replacing fossil-derived naphtha within existing petrochemical steam crackers, allowing new polyethylene and polypropylene to be manufactured from post-consumer plastic waste.

Naphtha is a light hydrocarbon fraction produced during crude oil refining and is the principal feedstock used by steam crackers throughout the global petrochemical industry. Steam crackers convert naphtha into ethylene and propylene, the fundamental building blocks used to manufacture virgin polyethylene and polypropylene. Consequently, for chemical recycling to become a truly circular process, pyrolysis oil must possess chemical characteristics that closely resemble conventional fossil-derived naphtha.

The principle of pyrolysis is straightforward. Plastic is heated in the absence of oxygen, causing the long polymer chains to break into smaller hydrocarbon molecules. These products are recovered as gases, condensable liquids (pyrolysis oil) and a small quantity of solid carbonaceous residue (char).

Unlike refining or purification processes, pyrolysis does not selectively remove contaminants from the feedstock. Instead, it redistributes the atoms already present within the incoming material into new chemical compounds.

Consequently, the elemental composition of the feedstock determines the elemental composition of the pyrolysis products.

A feedstock consisting almost entirely of polyethylene contains only two principal elements:

- **Carbon (C):**
- **Hydrogen (H):**

During pyrolysis these elements are converted predominantly into hydrocarbon molecules that closely resemble conventional petrochemical feedstocks.

However, modern post-consumer flexible packaging rarely consists solely of polyethylene. Through the incorporation of multilayer barrier polymers, nitrocellulose printing systems, paper labels, cellulose fibres, adhesives and functional coatings, additional elements are introduced into the feedstock, principally oxygen (O) and nitrogen (N).

These elements cannot disappear during pyrolysis. Oxygen remains distributed between oxygenated hydrocarbons, carbon monoxide (CO), carbon dioxide ($CO_2$), water and other oxygen-containing compounds. Nitrogen remains within nitrogen-containing hydrocarbons and gaseous nitrogen species. The resulting pyrolysis oil therefore progressively deviates from the composition of conventional fossil-derived naphtha.

The commercial significance of this chemistry becomes apparent when the pyrolysis oil is introduced into an existing steam cracker.

Steam crackers have been designed to process hydrocarbon feedstocks whose composition closely resembles conventional fossil-derived naphtha. Consequently, the quantity of recycled hydrocarbon that can be incorporated into a steam cracker is governed not only by the amount of pyrolysis oil produced, but by how closely that oil resembles conventional naphtha.

**CURRENT PRACTICE VS. PURIFIED FEEDSTOCK**

**1–2% → 30–40%**

of total steam cracker feed: the substitution range achievable from mixed post-consumer waste versus a highly purified polyethylene feedstock.

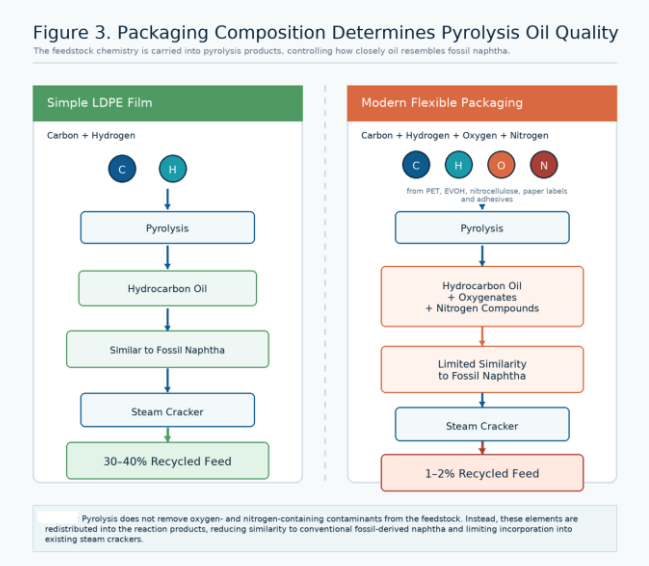


*Figure 2. Steam Cracker Substitution Economics — original artwork*

| ORIGINAL DIAGRAM DESCRIPTION | REDESIGNED DIAGRAM CONCEPT |
|---|---|
| A chart or schematic illustrating how recycled naphtha demand scales with steam cracker substitution rate, likely plotted against the tonnage figures underlying Table 1. | Rebuild as a horizontal step-bar chart in navy and accent blue: x-axis showing substitution rate (1%, 2%, 30%, 40%), y-axis showing tonnes/year on a single 800,000 tpa cracker. Use a light-grey reference bar for '1% — current practice' and a bold accent-blue bar for '30–40% — purified feedstock', with the tonnage figure printed directly on each bar. A single callout arrow should connect the two bars with the label '30x demand increase' to make the step-change commercial message immediate. |

Current industry practice typically limits pyrolysis oils produced from mixed post-consumer plastic waste to approximately 1–2% of total steam cracker feed. In contrast, pyrolysis oil produced from a highly purified polyethylene feedstock has the potential to increase recycled hydrocarbon substitution to approximately 30–40% of total cracker feed.

The commercial implications are substantial.

Steam crackers are built for large capacities to make economic sense. For a typical size 800,000 tonne per annum steam cracker, increasing recycled hydrocarbon substitution from 1% to 30% increases recycled feed demand from 8,000 tonnes per annum to 240,000 tonnes per annum.

The opportunity presented by feedstock purification is therefore not an incremental improvement in oil quality, but a step change in the quantity of recycled hydrocarbon that can be reintroduced into existing petrochemical infrastructure.

**Table 1. Recycled Hydrocarbon Demand for an 800,000 Tonne per Annum Steam Cracker**

| Steam Cracker Blend | Recycled Naphtha Required | Clean LDPE Feed Required (80% Liquid Yield) |
|---|---|---|
| 1% | 8,000 tonnes/year | 10,000 tonnes/year |
| 2% | 16,000 tonnes/year | 20,000 tonnes/year |
| 30% | 240,000 tonnes/year | 300,000 tonnes/year |
| 40% | 320,000 tonnes/year | 400,000 tonnes/year |

It is important to distinguish between liquid yield and product quality. Mixed post-consumer plastic waste may still produce substantial quantities of pyrolysis oil. However, if that oil contains elevated concentrations of oxygenated and nitrogen-containing compounds, its incorporation into conventional steam crackers remains limited. The principal challenge is therefore not simply producing a liquid hydrocarbon, but producing a hydrocarbon stream whose chemistry closely resembles fossil-derived naphtha.

This distinction forms the central hypothesis of this paper. Feedstock purification is not simply a pre-treatment operation; it is one of the principal determinants of pyrolysis oil quality and therefore of the quantity of recycled hydrocarbon that can ultimately be returned to virgin polymer production.

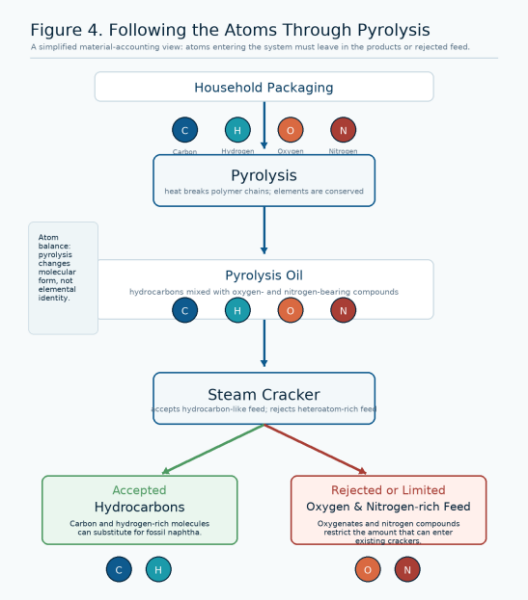


*Figure 3. Elemental Composition Concept — original artwork*

**ORIGINAL DIAGRAM DESCRIPTION**

A summary graphic positioned at the close of Section 3, likely illustrating the four-element framework (C, H, O, N) governing pyrolysis oil quality.

**REDESIGNED DIAGRAM CONCEPT**

Rebuild as a two-column comparison card: left card headed 'Desired — C, H' in accent blue with a hydrocarbon-chain icon; right card headed 'Undesired — O, N' in amber/red with a molecule icon showing heteroatoms. Beneath each, list the packaging sources feeding that column (from Table 3). This turns the abstract framework into an immediately scannable 'good vs. bad' reference card that recurs visually wherever elemental composition is discussed later in the document.

# 4. Sources of Oxygen- and Nitrogen-Containing Contamination in Flexible Packaging

Modern flexible plastic packaging has evolved into a highly engineered multi-material system designed to maximise product protection, shelf life, appearance and manufacturing efficiency. While these developments have delivered substantial benefits throughout the packaging supply chain, they have also introduced numerous materials that complicate both mechanical and chemical recycling.

From the perspective of pyrolysis, the individual function of each material is largely irrelevant. What determines the composition of the resulting pyrolysis oil is the elemental chemistry contributed by each component entering the reactor. Consequently, understanding the origin of oxygen- and nitrogen-containing contaminants within modern flexible packaging is fundamental to understanding the limitations of chemical recycling.

## 4.1 Multilayer Barrier Structures

Polyethylene possesses excellent moisture barrier properties and outstanding heat-sealing performance. However, its relatively low crystallinity, particularly in low-density polyethylene (LDPE), results in comparatively poor resistance to oxygen and aroma transmission. For many food packaging applications, polyethylene alone cannot provide the shelf life or product protection required.

To overcome these limitations, converters developed multilayer packaging structures in which polyethylene is combined with other polymers that provide specific functional properties.

Common examples include:

- **Polyethylene terephthalate (PET):** to improve stiffness, dimensional stability and printability.
- **Polyamide (PA):** to improve puncture resistance and mechanical strength.
- **Ethylene vinyl alcohol (EVOH):** to provide an excellent oxygen barrier.
- **Additional adhesive layers:** to bond otherwise incompatible polymers together.

Each of these materials performs an important function during the useful life of the package. However, each also introduces additional chemical elements into the recycling feedstock.

PET and EVOH contain significant quantities of oxygen within their molecular structures. Polyamide introduces nitrogen through its amide functional groups. Adhesive systems similarly contain oxygen-rich polymer chemistries that differ substantially from polyethylene.

During pyrolysis these materials do not behave as polyethylene. Instead of producing predominantly hydrocarbon molecules, they generate oxygenated and nitrogen-containing compounds that reduce the similarity of the resulting pyrolysis oil to conventional fossil-derived naphtha.

The incorporation of barrier polymers has therefore solved one engineering challenge while creating another. Materials introduced to improve food preservation and packaging performance become sources of contamination during chemical recycling.

## 4.2 Nitrocellulose Printing Systems

Whilst multilayer barrier polymers represent the most obvious source of oxygen- and nitrogen-containing contamination, modern flexible packaging also contains sophisticated printing systems that contribute significantly to feedstock chemistry.

Printing serves numerous functions beyond simple product decoration. It provides branding, regulatory information, product identification, traceability, barcodes and consumer instructions. Consequently, virtually every household flexible package entering the waste stream has been printed using one or more industrial printing processes.

The most widely used technologies for flexible packaging are flexographic and gravure printing. Both require ink systems capable of rapid drying, excellent adhesion to polyethylene and high production speeds. For many decades these requirements have been met using nitrocellulose-based ink systems.

Nitrocellulose has become one of the most widely used binders within flexible packaging inks because it provides:

- Rapid solvent evaporation
- Excellent print definition
- Good adhesion to corona-treated polyethylene
- High production speeds on flexographic and gravure presses
- Excellent resistance to blocking and abrasion
- Proven commercial performance across a wide range of packaging applications

Although the quantity of nitrocellulose present on an individual package is relatively small, it is present on a significant proportion of post-consumer flexible plastic packaging. When thousands of tonnes of printed household film are processed through a chemical recycling facility, the cumulative contribution of nitrocellulose becomes significant.

Unlike polyethylene, which consists almost entirely of carbon and hydrogen, nitrocellulose contains substantial quantities of both oxygen and nitrogen within its molecular structure.

During pyrolysis, nitrocellulose decomposes before polyethylene, producing a range of oxygen- and nitrogen-containing compounds rather than the predominantly hydrocarbon products generated from polyolefins.

These decomposition products include:

- Oxygenated hydrocarbons
- Carbon monoxide (CO)
- Carbon dioxide ($CO_2$)
- Nitrogen-containing organic compounds
- Nitrogen oxides ($NO_x$)
- Additional gaseous products

From the perspective of chemical recycling, nitrocellulose therefore represents more than simply a printing binder. It becomes a direct source of oxygen and nitrogen entering the pyrolysis reactor.

This distinction is important. Conventional discussions surrounding chemical recycling frequently focus on the polymer composition of flexible packaging, particularly the presence of PET, polyamide and EVOH. However, the printing system itself can also make a measurable contribution to feedstock contamination despite representing only a thin surface coating.

The resulting oxygen- and nitrogen-containing compounds reduce the similarity of the pyrolysis oil to conventional fossil-derived naphtha, increasing the concentration of heteroatoms within the recycled hydrocarbon stream and limiting its incorporation into existing steam crackers.

As the packaging industry increasingly transitions towards mono-material polyethylene structures, greater attention is also being given to printing systems that are compatible with both mechanical and chemical recycling.

New ink formulations and printing technologies are beginning to reduce dependence on traditional nitrocellulose systems. However, the existing stock of post-consumer flexible packaging generated over previous decades will continue to contain substantial quantities of nitrocellulose for many years.

Consequently, nitrocellulose should be regarded as one of the principal oxygen- and nitrogen-containing contaminants within post-consumer flexible plastic feedstocks and should be considered alongside multilayer polymers when evaluating feedstock quality for chemical recycling.

## 4.3 Paper Labels and Cellulose Fibres

Whilst the polymer composition of flexible packaging has received considerable attention within chemical recycling, comparatively little emphasis has been placed on the contribution of paper labels and cellulose fibres to feedstock contamination.

Paper labels remain widely used throughout the packaging industry for branding, regulatory information, product identification, promotional graphics and logistics. Although they typically represent only a small proportion of the overall package weight, they are present on a significant proportion of post-consumer flexible packaging entering the recycling stream.

Unlike polyethylene, paper is composed primarily of cellulose fibres. Cellulose is a naturally occurring polymer containing large numbers of hydroxyl (-OH) groups, making it highly polar and hydrophilic. These hydroxyl groups readily interact with water during the washing process, causing the cellulose fibres to hydrate, swell and become soft and highly flexible.

Flexible packaging is typically shredded before washing to produce flakes suitable for subsequent processing. During shredding, polyethylene flakes develop rough surfaces containing microscopic scratches, grooves and torn edges. As the hydrated cellulose fibres pass through the washing system, their flexibility allows them to conform to these surface irregularities and become mechanically entrapped within the polyethylene flake. Once embedded, the fibres are considerably more difficult to remove than larger paper fragments using conventional washing and screening systems.

The significance of this contamination extends beyond the cellulose itself. Cellulose fibres readily absorb and retain water, food residues, oils, inks, odorous organic compounds and other contaminants. They therefore act as carriers for a wide range of unwanted materials that remain associated with the polyethylene feedstock. In addition, the paper labels themselves typically carry printing inks, coatings and pressure-sensitive adhesive systems, introducing further oxygen-containing materials into the recycling stream.

During pyrolysis, cellulose follows a decomposition pathway entirely different from polyethylene. Instead of producing predominantly hydrocarbon molecules, it thermally decomposes to generate oxygen-containing compounds together with carbon monoxide (CO), carbon dioxide ($CO_2$), water vapour and carbonaceous residues (char). Consequently, even relatively small quantities of residual cellulose introduce additional oxygen into the chemical recycling feedstock and reduce the similarity of the resulting pyrolysis oil to conventional fossil-derived naphtha.

Unlike loose paper fragments, mechanically entrapped cellulose fibres cannot always be removed effectively by conventional washing and screening operations. Their persistence within the polyethylene feedstock means that oxygen-rich biomass, together with associated inks, adhesives and absorbed contaminants, is carried directly into the pyrolysis reactor where it contributes to the formation of oxygenated products.

Paper labels should therefore be regarded as more than a simple packaging accessory. They represent a significant source of oxygen-containing contamination which, together with the associated inks and adhesive systems, increases the chemical complexity of post-consumer flexible packaging and ultimately reduces the quality of the recycled hydrocarbon produced through pyrolysis.

## 4.4 Adhesive Systems

Adhesives are one of the least visible, yet most significant, contributors to the chemical complexity of modern flexible packaging. They are used extensively throughout flexible packaging manufacture to bond dissimilar polymer layers together, attach paper labels and provide pressure-sensitive adhesion for product identification and logistics.

Unlike polyethylene, adhesive systems are not simple hydrocarbon polymers. Modern packaging adhesives are typically based on complex acrylics, polyurethanes, polyester resins, synthetic rubbers and numerous proprietary polymer formulations. These materials are specifically engineered to provide strong adhesion between otherwise incompatible substrates whilst maintaining flexibility, durability and resistance to moisture and temperature.

Consequently, adhesive systems introduce additional oxygen-containing functional groups into the packaging structure. Although the overall mass of adhesive present within an individual package may appear relatively small, it is distributed throughout a substantial proportion of the flexible packaging waste stream and therefore represents a continuous source of contamination entering chemical recycling processes.

Pressure-sensitive label adhesives present a particular challenge. During shredding and washing, adhesive residues remain attached to both polyethylene flakes and cellulose fibres. In addition to introducing their own polymer chemistry into the feedstock, these adhesive residues also promote the retention of paper fibres, inks and other fine contaminants, making complete separation considerably more difficult.

During pyrolysis, adhesive polymers follow decomposition pathways that differ significantly from those of polyethylene. Rather than producing predominantly hydrocarbon molecules, they generate a broad spectrum of oxygen-containing organic compounds together with heavier condensable products and carbonaceous residues. These products contribute further oxygen-containing species to the pyrolysis oil, increasing its chemical complexity and reducing its similarity to conventional fossil-derived naphtha.

The cumulative effect of adhesive contamination is often underestimated because individual adhesive layers are thin. However, modern flexible packaging may contain multiple adhesive systems, including lamination adhesives, label adhesives, heat-seal coatings and other specialised bonding materials. Collectively, these materials make a measurable contribution to the oxygen content of the overall feedstock.

Adhesive systems therefore represent another important source of heteroatoms entering the pyrolysis process. When considered alongside multilayer barrier polymers, nitrocellulose printing systems and cellulose fibres, they illustrate how a package that appears to be predominantly polyethylene can, in reality, contain a complex mixture of materials whose combined chemistry ultimately determines the quality of the recycled hydrocarbon produced through pyrolysis.

The combined contribution of multilayer polymers, printing systems, paper labels and adhesives demonstrates that post-consumer flexible packaging should no longer be regarded as a simple polyethylene feedstock. Instead, it should be viewed as a chemically complex material in which the concentration of oxygen- and nitrogen-containing components is a primary determinant of pyrolysis oil quality. The following chapter therefore considers feedstock from an elemental rather than a polymer perspective, examining how carbon, hydrogen, oxygen and nitrogen collectively determine the composition and value of the resulting hydrocarbon products.

**Table 2. Packaging Components and Their Contribution to Pyrolysis Chemistry**

| Packaging Component | Primary Function | Principal Elements Introduced | Impact on Pyrolysis |
|---|---|---|---|
| LDPE | Seal layer | Carbon, Hydrogen | Desired hydrocarbon feedstock |
| PET | Stiffness, printability | Oxygen | Oxygenated compounds |

| Packaging Component | Primary Function | Principal Elements Introduced | Impact on Pyrolysis |
|---|---|---|---|
| EVOH | Oxygen barrier | Oxygen | Oxygenated compounds |
| PA | Strength, puncture resistance | Nitrogen | Nitrogen-containing compounds |
| Nitrocellulose | Ink binder | Oxygen, Nitrogen | Oxygenates, nitrogen compounds |
| Paper labels | Identification | Oxygen | Char, CO, $CO_2$, oxygenates |
| Cellulose fibres | Label residue | Oxygen | Oxygen-rich biomass |
| Adhesives | Bonding | Oxygen | Oxygenated hydrocarbons and heavy residues |

## 4.5 MDO Packaging — A New Generation of Flexible Packaging

The increasing demand for recyclable flexible packaging has accelerated the development of mono-material polyethylene structures designed to replace conventional multilayer laminates. One of the most significant developments has been the adoption of machine direction orientation (MDO) technology.

Unlike traditional multilayer packaging, which relies upon PET, polyamide and EVOH layers to provide stiffness, mechanical strength and gas barrier performance, MDO modifies the physical structure of polyethylene itself. During manufacture, the polyethylene film is stretched in the machine direction under carefully controlled temperature and tension. This orientation increases polymer chain alignment and crystallinity, improving stiffness, tensile strength and, to a lesser extent, gas barrier performance without introducing additional polymer layers.

As a result, many packaging applications that previously required PET/PE or PA/PE laminates can increasingly be manufactured using predominantly polyethylene structures. This represents a significant development for both mechanical and chemical recycling, as it reduces the quantity of oxygen- and nitrogen-containing barrier polymers entering the recycling stream.

The transition to MDO has also influenced printing technologies. Conventional multilayer laminates frequently relied on nitrocellulose-based primer and ink systems to achieve adequate print adhesion and durability. Many modern MDO polyethylene structures are now designed to accept printing directly onto the oriented polyethylene surface, or employ alternative print systems specifically developed for mono-material recyclable packaging. Although nitrocellulose has not disappeared from the packaging industry, its use is expected to decline as recyclable mono-material packaging becomes more widely adopted.

From the perspective of chemical recycling, this transition is particularly significant. MDO packaging reduces two of the principal sources of oxygen- and nitrogen-containing contamination simultaneously: multilayer barrier polymers and traditional nitrocellulose-based printing systems. The resulting feedstock more closely approaches the elemental composition of polyethylene itself, increasing the potential to manufacture pyrolysis oils with greater similarity to conventional fossil-derived naphtha.

The widespread adoption of MDO technology therefore represents more than an evolution in packaging design. It demonstrates that future packaging can be engineered not only for product performance, but also for improved compatibility with both mechanical and chemical recycling. As the proportion of mono-material MDO packaging increases within the household waste stream, the quality of future chemical recycling feedstocks can be expected to improve correspondingly.

# 5. Feedstock Chemistry — Why Elemental Composition Matters

The previous chapter examined the principal components of modern flexible packaging that contribute to feedstock contamination. From the perspective of chemical recycling, however, the origin of these materials is less important than their elemental composition.

Pyrolysis is a thermal conversion process. It does not distinguish between polyethylene, polyamide, paper, adhesives or printing systems. Nor does it distinguish whether oxygen originates from EVOH, cellulose, polyester or an acrylic adhesive. During thermal cracking, all materials are converted simultaneously, and the resulting products are determined by the elements present within the feedstock.

Consequently, the chemistry of the feedstock can be considered in terms of four principal elements:

- **Carbon (C):**
- **Hydrogen (H):**
- **Oxygen (O):**
- **Nitrogen (N):**

Carbon and hydrogen form the basis of all hydrocarbon fuels and petrochemical feedstocks. A feedstock composed almost entirely of carbon and hydrogen will therefore produce a pyrolysis oil dominated by hydrocarbon molecules closely resembling conventional fossil-derived naphtha.

Oxygen and nitrogen behave very differently.

Unlike carbon and hydrogen, these elements do not contribute to the production of simple hydrocarbon molecules. Instead, they become incorporated into oxygen-containing and nitrogen-containing reaction products, increasing the chemical complexity of the resulting pyrolysis oil.

The objective of feedstock preparation is therefore not simply to maximise polyethylene concentration. It is to maximise the proportion of carbon and hydrogen entering the pyrolysis reactor whilst minimising oxygen- and nitrogen-containing materials.

This distinction is illustrated in Table 3.

**Table 3. Principal Elements Governing Pyrolysis Oil Quality**

| Element | Principal Sources in Flexible Packaging | Influence on Pyrolysis |
|---|---|---|
| Carbon | Polyethylene, polypropylene | Forms the hydrocarbon backbone of the pyrolysis oil. |
| Hydrogen | Polyethylene, polypropylene and other polymers | Combines with carbon to produce hydrocarbon molecules resembling fossil-derived naphtha. |
| Oxygen | PET, EVOH, cellulose, paper labels, adhesives, coatings, printing systems | Produces oxygen-containing compounds together with CO, $CO_2$ and water, reducing similarity to conventional naphtha. |
| Nitrogen | Polyamide, nitrocellulose and selected additives | Produces nitrogen-containing compounds and gaseous nitrogen species, reducing hydrocarbon purity. |

From a chemical perspective, oxygen and nitrogen may therefore be regarded as undesirable contaminants within a pyrolysis feedstock. Whilst they perform valuable functions during the useful life of the package, they do not contribute to the production of high-quality hydrocarbon feedstocks for steam cracking.

It follows that two flexible packaging streams containing identical polyethylene contents may produce pyrolysis oils of significantly different quality if their concentrations of oxygen- and nitrogen-containing materials differ.

This distinction has important implications for chemical recycling. Feedstocks are commonly classified according to polymer composition, for example polyethylene, polypropylene, PET or polyamide. Whilst this approach is appropriate for mechanical recycling, it does not fully describe the behaviour of the material during pyrolysis.

For chemical recycling, a more meaningful measure of feedstock quality is its elemental composition. A feedstock containing high concentrations of carbon and hydrogen and low concentrations of oxygen and nitrogen will inevitably produce a pyrolysis oil more closely resembling fossil-derived naphtha than an otherwise similar feedstock containing higher concentrations of heteroatoms.

This shift in perspective — from polymer composition to elemental chemistry — provides a more fundamental basis for understanding pyrolysis performance. Rather than asking which polymers are present within the feedstock, the more important question becomes how much oxygen and nitrogen they collectively introduce into the chemical recycling process.

Feedstock purification should therefore be viewed not simply as a sorting operation, but as a process for engineering the elemental chemistry of the incoming material. By reducing oxygen- and nitrogen-containing contaminants before thermal conversion, the resulting hydrocarbon stream more closely approaches the composition required for high-rate substitution of fossil-derived naphtha within existing steam crackers.

# 6. The Influence of Oxygen and Nitrogen on Pyrolysis Oil Quality

The previous chapter demonstrated that the chemistry of the pyrolysis products is determined by the elemental composition of the incoming feedstock. Carbon and hydrogen are converted predominantly into hydrocarbon molecules, whilst oxygen and nitrogen are redistributed into oxygen-containing and nitrogen-containing reaction products.

The consequence is that two feedstocks may produce similar quantities of pyrolysis oil whilst producing hydrocarbon streams of significantly different quality and commercial value.

This distinction is fundamental to understanding chemical recycling.

## 6.1 The Effect of Oxygen

Oxygen is introduced into post-consumer flexible packaging through a variety of materials including PET, EVOH, cellulose, paper labels, adhesive systems, coatings and numerous functional additives.

During pyrolysis, this oxygen does not disappear. Instead, it is incorporated into a wide range of oxygen-containing compounds including alcohols, aldehydes, ketones, phenols, carboxylic acids, esters, together with carbon monoxide (CO), carbon dioxide ($CO_2$) and water.

These compounds differ fundamentally from the hydrocarbon molecules that constitute conventional fossil-derived naphtha. As the oxygen concentration within the feedstock increases, the resulting pyrolysis oil progressively departs from the hydrocarbon composition required by existing petrochemical steam crackers.

The principal challenge is therefore not the production of liquid hydrocarbons, but the production of hydrocarbons with sufficiently low oxygen content to behave as a direct substitute for fossil-derived naphtha.

## 6.2 The Effect of Nitrogen

Nitrogen enters flexible packaging primarily through polyamide barrier layers, nitrocellulose printing systems and selected functional additives.

During thermal cracking, these nitrogen atoms are redistributed into nitrogen-containing organic compounds together with gaseous nitrogen species.

Although the concentration of nitrogen within the feedstock is typically much lower than carbon or hydrogen, even relatively small quantities contribute to the chemical complexity of the resulting pyrolysis oil. The presence of nitrogen-containing compounds further reduces the similarity of the recycled hydrocarbon to conventional fossil-derived naphtha and contributes to the limitation of steam cracker blending rates.

## 6.3 Pyrolysis Oil Quality

Chemical recycling literature frequently reports liquid yield as one of the principal measures of process performance. Whilst liquid yield is clearly important from an operational perspective, it provides only limited information regarding the commercial value of the product.

Two feedstocks may each produce approximately 80% liquid yield. However, if one feedstock consists predominantly of clean polyethylene and the second contains significant concentrations of oxygen- and nitrogen-containing contaminants, the resulting oils will possess fundamentally different chemical compositions.

The first will consist predominantly of hydrocarbon molecules approaching the composition of conventional fossil-derived naphtha.

The second may produce a similar quantity of liquid product, but that liquid will also contain oxygenated compounds and nitrogen-containing compounds originating directly from the feedstock.

Consequently, the commercial value of the two products is very different despite their similar liquid yields.

The objective of chemical recycling should therefore not be viewed as maximising liquid yield, but as maximising the production of hydrocarbons capable of replacing fossil-derived naphtha within existing petrochemical infrastructure.

> *Two feedstocks may each produce approximately 80% liquid yield — yet possess fundamentally different commercial value. Quality, not yield, is the measure that matters.*

## 6.4 Steam Cracker Acceptance

Steam crackers have been optimised over many decades to process hydrocarbon feedstocks with tightly controlled chemical compositions. The closer a recycled hydrocarbon resembles conventional fossil-derived naphtha, the greater the proportion that can be incorporated into existing cracker feed.

Current industry practice typically limits pyrolysis oils produced from mixed post-consumer flexible plastic waste to approximately 1–2% of total steam cracker feed. In contrast, pyrolysis oil produced from a highly purified polyethylene feedstock has the potential to achieve recycled hydrocarbon substitution levels of approximately 30–40%.

The important distinction is that both feedstocks may produce similar quantities of liquid product. The difference lies not in the quantity of oil produced, but in its chemical composition and its ability to replace fossil-derived naphtha within existing steam crackers.

The success of chemical recycling should therefore be measured not simply by liquid yield, but by the quantity of recycled hydrocarbon that can ultimately be incorporated into virgin polymer production. From this perspective, feedstock purity becomes one of the principal determinants of both the technical and commercial performance of chemical recycling.

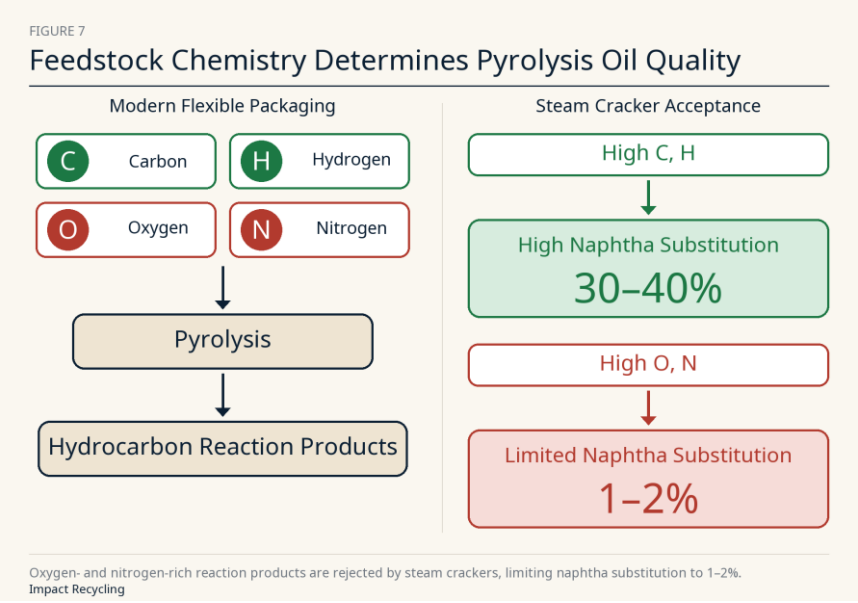


*Figure 4. Steam Cracker Acceptance Pathway — original artwork*

| ORIGINAL DIAGRAM DESCRIPTION | REDESIGNED DIAGRAM CONCEPT |
|---|---|
| A process diagram positioned at the close of Section 6, likely tracing the pathway from feedstock quality through | Rebuild as a horizontal five-stage process flow in the brand palette (navy nodes, accent-blue connecting arrows, pale-grey background): Mixed Waste → |

| | |
|---|---|
| pyrolysis to steam cracker acceptance and final polymer output. | Purification (BOSS + HydroDyn) → Pyrolysis → Steam Cracker → Virgin-Quality Polymer. Beneath the 'Steam Cracker' node, add a small split showing the two substitution-rate outcomes (1–2% vs 30–40%) so the diagram visually pays off the economics established earlier in the document. |

# 7. Steam Crackers — The Importance of Naphtha Substitution

The ultimate objective of chemical recycling is not the production of pyrolysis oil, but the manufacture of new virgin-quality polymers. Pyrolysis represents only one stage within a much larger petrochemical value chain.

Conventional steam crackers form the foundation of global polyolefin production. These facilities thermally crack fossil-derived naphtha to produce ethylene and propylene, which are subsequently polymerised to manufacture polyethylene and polypropylene.

Chemical recycling seeks to substitute a proportion of this fossil-derived naphtha with recycled hydrocarbons produced from post-consumer plastic waste. Success should therefore be measured not by the quantity of pyrolysis oil produced, but by the quantity of recycled hydrocarbon that can ultimately replace fossil-derived naphtha within existing petrochemical infrastructure.

This distinction is fundamental.

A pyrolysis plant may produce a high liquid yield, but if the resulting oil contains elevated concentrations of oxygenated and nitrogen-containing compounds, only a relatively small proportion can be incorporated into conventional steam cracker feed. Conversely, a hydrocarbon produced from a highly purified polyethylene feedstock more closely resembles fossil-derived naphtha and can therefore be introduced at substantially higher substitution rates.

Current industry practice typically limits pyrolysis oils produced from mixed post-consumer flexible plastic waste to approximately 1–2% of total steam cracker feed. In contrast, pyrolysis oils produced from highly purified polyethylene feedstocks have the potential to achieve substitution levels of approximately 30–40%.

The commercial significance of this difference is considerable.

**Table 4. Recycled Hydrocarbon Demand for an 800,000 Tonne per Annum Steam Cracker**

| Steam Cracker Blend | Recycled Naphtha Required | Clean LDPE Feed Required (80% Liquid Yield) |
|---|---|---|
| 1% | 8,000 tonnes/year | 10,000 tonnes/year |
| 2% | 16,000 tonnes/year | 20,000 tonnes/year |
| 30% | 240,000 tonnes/year | 300,000 tonnes/year |
| 40% | 320,000 tonnes/year | 400,000 tonnes/year |

Increasing recycled hydrocarbon substitution from 1% to 30% increases recycled naphtha demand by a factor of thirty. For a single 800,000 tonne per annum steam cracker, this represents an increase from only 8,000 tonnes of recycled hydrocarbon per year to approximately 240,000 tonnes per year.

The implications extend far beyond the operation of an individual pyrolysis facility. Higher substitution rates create demand for substantially greater quantities of post-consumer plastic waste, increasing the amount of material that can be returned to virgin-quality polymer production and reducing dependence on fossil-derived raw materials.

From this perspective, feedstock purification becomes a strategic enabler of circularity. Every reduction in oxygen- and nitrogen-containing contamination increases the similarity of the resulting hydrocarbon to conventional naphtha and therefore increases the potential proportion of recycled carbon that can be reintroduced into existing petrochemical infrastructure.

The opportunity is therefore not simply to produce a better pyrolysis oil, but to increase the quantity of post-consumer plastic that can complete the journey from household packaging back into new food-contact polyethylene and polypropylene through existing steam cracker infrastructure.

This represents one of the principal opportunities for achieving the recycled-content targets established under PPWR while utilising the existing global petrochemical manufacturing base.

# 8. Principles of Feedstock Purification

The previous chapters have demonstrated that the quality of a pyrolysis oil is fundamentally determined by the elemental composition of the incoming feedstock. Carbon and hydrogen form the desired hydrocarbon products, whilst oxygen and nitrogen are redistributed into oxygenated and nitrogen-containing compounds that reduce the similarity of the resulting oil to conventional fossil-derived naphtha.

It follows that improving pyrolysis oil quality begins before the material enters the pyrolysis reactor.

The objective of feedstock purification is therefore not simply to remove contamination. It is to engineer a feedstock whose elemental composition has been optimised for chemical recycling by maximising carbon and hydrogen whilst minimising oxygen- and nitrogen-containing materials.

From a chemical recycling perspective, feedstock preparation should target four principal sources of contamination:

- Multilayer barrier polymers containing oxygen- and nitrogen-rich materials such as PET, EVOH and polyamide.
- Nitrocellulose printing systems and associated coatings.
- Paper labels, cellulose fibres and associated printing materials.
- Lamination adhesives and pressure-sensitive label adhesives.

Unlike conventional waste sorting, which seeks to improve the overall quality of a recyclable material, feedstock purification seeks to improve the chemistry of the material entering the pyrolysis reactor. The objective is not simply a cleaner polyethylene stream, but a feedstock capable of producing a hydrocarbon oil whose composition approaches that of conventional fossil-derived naphtha.

This distinction is important because two polyethylene-rich feedstocks may contain very different concentrations of oxygen- and nitrogen-containing contaminants. Although both may produce similar liquid yields during pyrolysis, the resulting hydrocarbon streams can differ significantly in their suitability for incorporation into existing steam crackers.

Feedstock purification should therefore be viewed as an integral part of the chemical recycling process rather than a separate pre-treatment operation. Every reduction in oxygen- and nitrogen-containing contamination improves the hydrocarbon purity of the resulting pyrolysis oil and increases the potential substitution of fossil-derived naphtha within existing petrochemical infrastructure.

The characteristics of an ideal chemical recycling feedstock are summarised in Table 5.

**Table 5. Characteristics of an Ideal Feedstock for Chemical Recycling**

| Property | Preferred Characteristic |
|---|---|
| Polymer composition | Predominantly polyethylene |
| Carbon content | High |
| Hydrogen content | High |
| Oxygen content | As low as practicable |
| Nitrogen content | As low as practicable |
| Cellulose contamination | Minimal |
| Nitrocellulose contamination | Minimal |
| Adhesive contamination | Minimal |

| Property | Preferred Characteristic |
|---|---|
| Chlorine contamination | Minimal |
| Moisture | Low |
| Ash | Low |

From this perspective, feedstock purification becomes a process of engineering the elemental chemistry of the incoming material rather than simply sorting waste plastics.

# 9. Practical Technologies for Feedstock Purification

Producing a feedstock suitable for high-quality chemical recycling requires the sequential removal of different classes of contaminants. No single technology is capable of removing every contaminant present within modern post-consumer flexible packaging. Instead, a combination of complementary separation and cleaning technologies is required to progressively improve feedstock purity before pyrolysis.

The first stage of purification involves the removal of multilayer structures and non-polyolefin materials. These include PET, EVOH, polyamide and other barrier polymers that introduce oxygen and nitrogen into the feedstock. Their removal significantly increases the polyethylene concentration whilst reducing the principal sources of heteroatom contamination.

Density-based separation technologies such as the BOSS (Baffled Oscillation Separation System) have been developed specifically to separate mono-material polyethylene films from heavier multilayer packaging using differences in density rather than optical properties. By removing multilayer structures before pyrolysis, the oxygen- and nitrogen-containing polymer fraction entering the reactor is substantially reduced.

Following polymer separation, further purification is required to remove contaminants associated with the surface of the polyethylene flakes. These include paper labels, cellulose fibres, pressure-sensitive adhesives, printing residues and absorbed organic contaminants that remain attached after conventional washing.

Hydrodynamic cleaning technologies such as HydroDyn provide an additional purification stage by generating intense hydraulic shear within the washing process. This action removes mechanically entrapped cellulose fibres, adhesive residues and fine surface contaminants that are difficult to eliminate using conventional friction washing alone. The result is a substantially cleaner polyethylene feedstock with lower concentrations of oxygen-rich biomass and associated printing residues.

The combination of polymer separation followed by intensive surface cleaning addresses two fundamentally different contamination mechanisms. The first removes unwanted polymers that introduce oxygen and nitrogen through their molecular structure. The second removes surface contaminants that introduce additional oxygen-containing materials together with odours, inks and adhesive residues.

TWO COMPLEMENTARY PURIFICATION STAGES

## BOSS + HydroDyn

BOSS removes multilayer, non-target polymers by density. HydroDyn then removes surface-entrapped cellulose fibres, adhesive residues and fine contaminants that washing alone leaves behind.

The objective is not simply to produce a visually cleaner plastic flake. The objective is to engineer a polyethylene feedstock whose elemental composition approaches that of virgin polyethylene by maximising carbon and hydrogen whilst minimising oxygen- and nitrogen-containing contaminants.

This approach has important implications for the future of chemical recycling. Improvements in feedstock quality directly influence the composition of the resulting pyrolysis oil, enabling higher rates of recycled hydrocarbon substitution within existing steam crackers and increasing the quantity of post-consumer plastic capable of returning to virgin-quality polymer production.

As recycled-content requirements continue to increase under PPWR, the availability of high-purity chemical recycling feedstocks will become increasingly important. Mechanical recycling and chemical recycling should therefore be viewed as complementary technologies. Mechanical recycling provides the preferred route for suitable natural and lightly coloured polyethylene streams, whilst chemical recycling offers a route for recovering value from

the remaining coloured and heavily printed flexible packaging fraction. In both cases, the quality of the final product is fundamentally determined by the quality of the feedstock entering the recycling process.

The central conclusion of this paper is therefore that feedstock purity is not simply a pre-treatment consideration; it is one of the principal determinants of successful chemical recycling. By engineering the chemistry of the feedstock before pyrolysis, significantly greater quantities of recycled hydrocarbon can be returned to existing petrochemical infrastructure, supporting the transition towards a genuinely circular plastics economy.

The future success of chemical recycling will not be determined solely by the efficiency of thermal cracking, but by the ability to engineer feedstocks whose chemistry enables meaningful replacement of fossil-derived naphtha within existing steam crackers.

> *The future success of chemical recycling will not be determined solely by the efficiency of thermal cracking, but by the ability to engineer feedstocks whose chemistry enables meaningful replacement of fossil-derived naphtha within existing steam crackers.*