PLASTIC WASTE MANAGEMENT WITH A FOCUS ON POLYMERS: CURED RESINS, CONDENSATION PRODUCTS, AND FLUORINATED POLYMERS

Technical Report with Policy Recommendations

GRID ARENDAL

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Technical Report with Policy Recommendations

GRID-Arendal is a non-profit environmental communications centre based in Norway transforming environmental data into innovative, science-based information products and provide capacity-building services that enable better environmental governance. We aim to inform and activate a global audience and motivate decision-makers to effect positive change. Our vision is a society that understands, values, and protects the environment on which it depends.

IPEN is a global network of more than 600 Participating Organizations in over 125 countries, primarily developing and transition countries. IPEN works to establish and implement safe chemicals policies and practices that protect human health and the environment, for a toxics-free future for all.

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TABLE OF CONTENTS

LIST OF ACRONYMS

BPA	Bisphenol A
FEP	Fluorinated Ethylene Propylene
GFRP	Glass Fiber Reinforced Polymer
HCN	Hydrogen Cyanide
HNCO	Isocyanate
ISO	The International Organization for Standards
IUPAC	The International Union of Pure and Applied Chemistry
MARPOL	The International Convention for the Prevention of Pollution from Ships
MDF	Medium-Density Fibreboards
MF	Melamine Formaldehyde
MFA	Tetrafluoroethylene/Perfluoromethyl Vinyl Ether
NH3	Ammonia
NOx	Nitrogen Oxides
PF	Phenol Formaldehyde
PFA	Tetrafluoroethylene/Perfluoroalkyl Vinyl Ether
PFA and MFA	Perfluoroalkoxy Alkanes
PIC	Prior Informed Consent
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidenefluoride
PVF	Polyvinylfluoride
TFE	Tetrafluoroethylene
UF	Urea Formaldehyde
UNEA	The United Nations Environment Assembly

EXECUTIVE SUMMARY

Plastic production continues to expand every year, necessitating stronger actions to tackle the impact of plastics on the triple planetary crises of climate change, biodiversity loss, and pollution.

Growing concerns around plastic pollution triggered amendments of the Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal, the only international policy instrument governing plastic waste management.

The Basel Convention promotes the environmentally sound management of waste by taking all practicable measures to ensure that hazardous and other wastes are handled in a way that protects human health and the environment from potential adverse effects. This is guided by the waste management hierarchy where prevention and minimization are the preferred options, followed by reuse and recycling as other priority options.

The plastic waste amendments to the Basel Convention mandate Prior Informed Consent (PIC) for the export of all plastic waste under Annexes II and VIII. However, exemptions were included for certain types of plastic wastes "…destined for recycling in an environmentally sound manner and almost free from contamination and other types of wastes."

This report aims to provide a consolidated review, based on the scientific literature, examining the assumption that cured resins, condensation products, and fluorinated polymers meet the exemption criteria.

Cured resins are rigid thermoset plastics that are often used as glues, for example, when producing plywood. Condensation products are plastics such as polyamides and polyesters, which are often used in textiles. Fluorinated polymers are part of the large group of per- and polyfluoroalkyl substances (PFAS) and are used, for example, to create non-stick surfaces and corrosion-resistant linings in pipes and vessels.

This report reveals that these exempted polymers – cured resins, condensation products, and fluorinated polymers – are often integral parts of complexly designed industrial and consumer products and face challenges in being recycled in an environmentally sound manner.

Based on the above, the following policy recommendations are suggested:

- Plastics that cannot be produced, used, or recycled in a safe and sustainable manner should be phased out, as they are incompatible with a circular economy approach and can harm human health and the environment. This includes plastics that contain hazardous chemicals as well as plastics that are integral parts of products and are not feasible to extract, such as cured resins, condensation products, and fluorinated polymers.
- The polluter pays principle must be adequately legislated and implemented as part of a holistic, system-based approach to plastic waste management, including the internalisation of waste management costs by producers of plastics and plastic products.
- The exemptions from the Basel Convention Prior Informed Consent procedure for cured resins, condensation products, and fluorinated polymers should be removed, as these exempted polymers are typically difficult to recycle in an environmentally sound manner or to keep almost free from contamination and other types of wastes.
- In addition, given the hazardous properties of many of these plastics when openly burned, incinerated, or landfilled, they should be classified as hazardous waste and controlled under the Basel Ban Amendment.
- Finally, the Conference of the Parties to the Basel Convention concluded in 2023 that chemical conversion, often referred to as chemical recycling, has not been proven to be an environmentally sound management practice. Until independent scientific evidence demonstrates otherwise, it should not be seen as a viable option for plastic waste.

INTRODUCTION

There is growing attention to and increased international efforts on the sound management of plastic waste. In the past 50 years, the production of plastic has increased exponentially, reaching almost 460 million tons per year in 2019 (OECD, 2022). It is estimated that in 2060, the total annual production will have expanded to 1.23 billion tonnes under a "business-as-usual" scenario (OECD, 2022). Concerns over the growing production of plastic, the resulting waste, and its detrimental impacts on human health and the environment have given rise to discussions around implementation of circular economy approaches that promote the reduction, reuse, and recycling of materials, components, and products.

The Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal is the only international policy instrument that governs plastic waste management, regulates the international movement of hazardous and other wastes, and supports Parties in managing their waste in an environmentally sound manner.

This report looks at the three major types of plastic waste that are exempted under certain circumstances from the Prior Informed Consent (PIC) procedure required under the Basel Convention: cured resins, condensation products, and fluoropolymers.

In 2019, amendments to the Basel Convention were adopted to mandate Prior Informed Consent for the export of all plastic waste under Annexes II and VIII. These amendments came into force in 2021. However, exemptions were included for certain types of plastic wastes "*...destined for recycling in an environmentally sound manner and almost free from contamination and other types of wastes*" (SBC, 2023).

This technical report provides an analysis of the state of the science and the accuracy of the underlying assumption of circularity and environmentally sound waste management of the three major groups of plastics covered by this exemption:

- Cured resins: including Urea Formaldehyde (UF) resin, Phenol formaldehyde (PF) resin, Melamine formaldehyde (MF) resin, Epoxy resins, and Alkyd resins;
- Condensation products: including polyamides and unsaturated polyester resins; and
- Fluoropolymers.

The report provides information about common uses of these polymers and delves deeper into recycling options and associated challenges. The report aims to provide a consolidated review, based on the scientific literature, to examine the assumption that the above-mentioned polymers meet the exemption criteria.

This question has also become increasingly relevant in the context of the ongoing negotiations of the new global legally binding instrument to end plastic pollution. The United Nations Environment Assembly (UNEA) resolution 5/14 called to eliminate plastic pollution considering a full lifecycle approach to plastics including production, consumption, and waste management phases.

According to the Basel Convention, environmentally sound management (ESM) of waste means taking all practicable steps to ensure that hazardous wastes or other wastes are managed in a manner which will protect human health and the environment against the adverse effects which may result from such wastes. The waste management hierarchy serves as a guiding principle for the environmentally sound management of waste, emphasizing prevention, minimization, reuse, and recycling as priorities over other recovery operations – such as energy recovery – and final disposal (Basel Convention, 2023).

Everyday plastic products are increasingly becoming too complex in their designs to be managed in an environmentally sound manner at the end of their lifecycles. Consumer products are often made of different types of plastics. In addition, products can be made of composite materials where plastics become integral parts of product design. Consumer applications such as electrical and electronic equipment, products such as kitchenware with non-stick coating, and construction materials such as plywood and fibreboards are among applications where plastics are used as integral parts of the product design.

Waste management options for such consumer products become limited to incineration or landfill management. Disposal of waste containing cured resins, condensation products, and fluoropolymers may lead to environmental contamination. For instance, wastes containing urea formaldehyde resins used in production of medium-density fibreboards (MDF) can leach into subsoil water and lead to the formation of methane, a potent greenhouse gas.

Many countries are looking towards a circular economy approach to respond to increasing demand to use resources in more sustainable ways and prevent plastic pollution. Circular economy approaches include considering policies that encourage industry to move towards circular-by-design principals. These policies may promote designing plastic products with recyclability in mind while understanding that recycling of plastics is not a complete solution.

Addressing plastic waste requires a holistic approach, starting with a systematic transformation of plastic products and consumption. Principle 16 of the Rio Declaration on Environment and Development states that “National authorities should endeavour to promote the internalization of environmental costs and the use of economic instruments, taking into account the approach that the polluter should, in principle, bear the cost of pollution, with due regard to the public interest and without distorting international trade and investment”. This principle has not been translated into policies or regulations in most regions and countries.

In moving forward, it is important to understand waste management options and the environmental implications of certain plastic recycling methods. This report demonstrates that there are limited recycling options for post-industrial waste (i.e., waste produced during manufacturing processes) containing cured resins, condensation products, and fluoropolymers. Post-consumer plastic waste containing these polymers are typically destined for incineration or landfills. Combustion for the purpose of energy recovery often results in pollutant emissions that need to be reduced with costly purification and filtering systems (Risholm-Sundman and Vestin, 2005). Pyrolysis (a chemical conversion technology often called chemical recycling) is also a very energy-intensive process that may generate end products that are toxic. For instance, pyrolysis of melamine formaldehyde resin generates hydrocyanic acid that needs to be captured and disposed of in a safe and sound manner (Girods et al, 2008a; Girods et al, 2008b). Chemical conversion (commonly known as chemical recycling) has not been proven to be an environmentally sound management technique and typically creates hazardous by-products or waste that need to be further treated. For example, the hydrothermal hydrolysis of urea formaldehyde resins generates formaldehyde in hydrolysed solution, which becomes new hazardous waste (Liu, 2018).

CHARACTERISTICS OF POLYMERS AND THEIR APPLICATIONS

Plastic is a synthetic or modified natural material. Plastics have been defined in various ways depending on the context. For example, their definition differs in materials science compared to international governance.

Currently, there is no consensus on a single definition of plastics and which materials should be included in the term. Due to the wide diversity of polymer types, classifying them comprehensively is challenging (Basel Convention, 2023). However, the most common classification is based on separating them into thermoplastics and thermosets based on their processing methods and behaviour when heated.

Thermoplastics are polymers that soften when heated and harden upon cooling. In contrast, thermosets undergo a chemical reaction during processing which prevents them from being re-softened and re-moulded. This difference determines their flexibility in terms of reshaping and recycling. In addition, as consumer products and their designs become increasingly complex, featuring multi-layered structures and various additives, identifying polymers or types of polymers suitable for environmentally sound waste management becomes increasingly challenging.

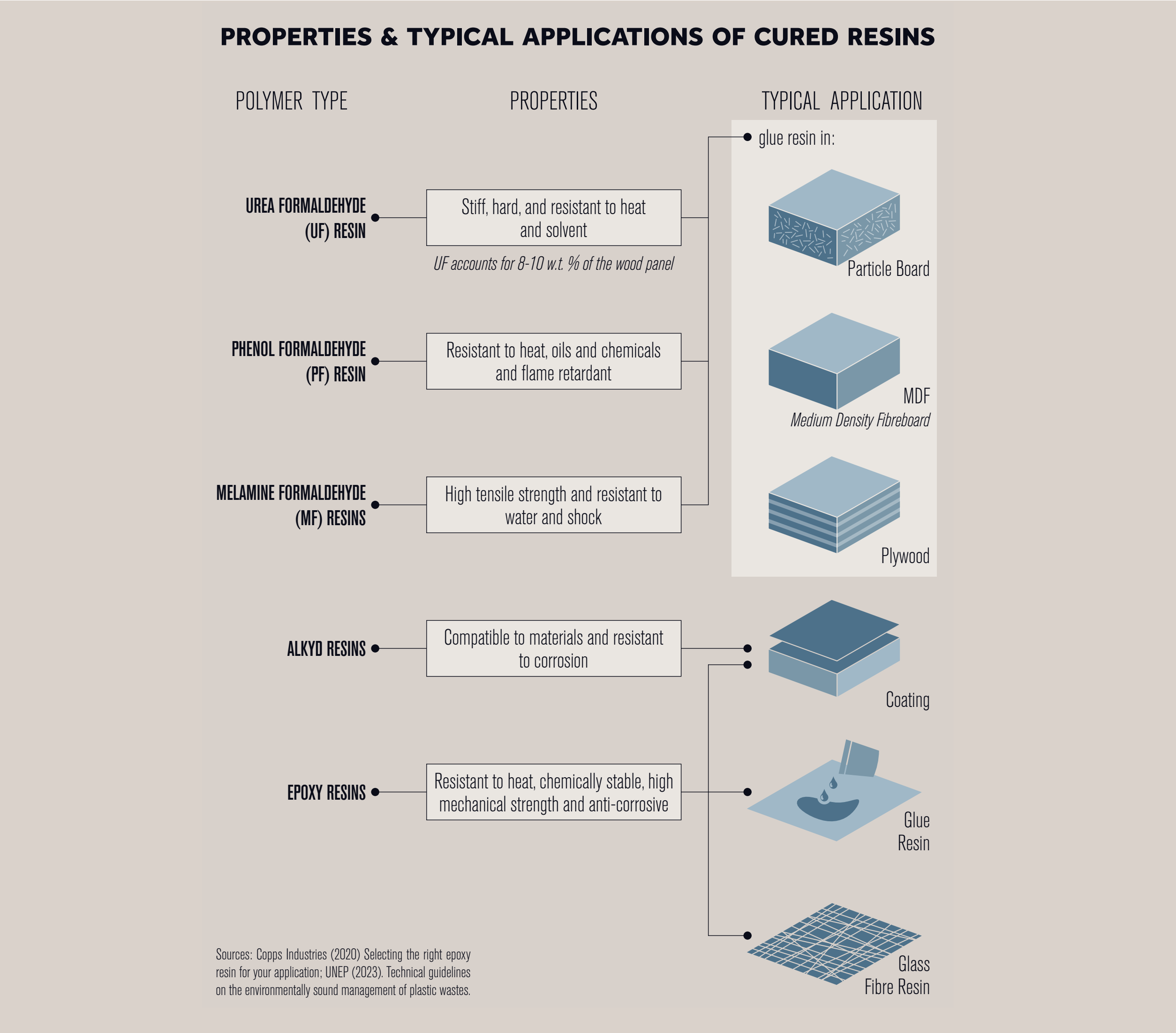
According to the International Union of Pure and Applied Chemistry (IUPAC), the definition of polymers is based on the composition of molecules comprising the multiple repetition of molecular units. By contrast, the International Organization for Standards (ISO) and the International Convention for the Prevention of Pollution from Ships (MARPOL) define plastics as material containing polymer chains which at some stage is processed into a final product.

- Polymers are substances composed of large molecules with molecular weights ranging from a few thousand to as high as millions of grams/moles which essentially comprises the multiple repetition of units derived, actually or conceptually, from molecules of low relative molecular mass (IUPAC, 2025).
- Plastic is defined as “material which contains as an essential ingredient a high polymer and which, at some stage in its processing into finished products, can be shaped by flow” (ISO, 2020).
- Plastics are solid materials that contain as an essential ingredient one or more high-molecular-mass polymers, and which are formed (shaped) by heat and/or pressure during either the manufacture of the polymer or the fabrication into a finished product (MARPOL 2011).

The amendments made to the Basel Convention explicitly include cured resins, condensation products, and fluorinated polymers as plastic wastes. The specifications of these plastics are detailed in the following sub-sections.

CURED RESINS

Cured resins are thermoset plastics formed by cross-linking polymer chains (Basel Convention, 2023). This includes a hardening step that is accomplished through a chemical process known as curing, which can be brought on by heating or by the addition of a curing agent (Crosky, 2014).



Sources: Copps Industries (2020) Selecting the right epoxy resin for your application; UNEP (2023). Technical guidelines on the environmentally sound management of plastic wastes.

Figure 1: Properties & typical applications of cured resins

Therefore, cured resins are rigid and do not flow on heating. The following examples from this group are all entries in Annexes II and IX of the Basel Convention and are discussed in this report: urea formaldehyde (UF) resins, phenol formaldehyde (PF) resins, melamine formaldehyde (MF) resin, epoxy resins, and alkyd resins. These products are classified as thermosets and consequently face additional challenges for re-moulding.

Cured resins come in a variety of types and applications based on their heat and chemical resistance properties. They are used in construction, coatings, electronics, homeware, building materials, food contact materials, and the automotive sector. The worldwide production and use of cured resins is a multi-billion-dollar market and is projected to increase in coming years. An overview of common uses is provided in Figure 1.

Urea formaldehyde (UF) resins are aminoplastic thermosetting resins that are synthesised by the reaction between formaldehyde and urea. They are rigid, fast-curing resins, resistant to heat and solvents. With these properties in mind, these resins have broad applications in wood-based panels, coatings, moulding compositions, and adhesives. The applications for the moulding products includes electrical equipment, buttons, cups, and bottles (Bliznakov, 2000). Another notable application of these resins is in the clothing industry to create wrinkle-resistant fabrics (Fowler et al., 1992; Formacare, 2019). Applications of these resins as adhesives include wood-based panels, particle board, medium density fibreboard (MDF), and plywood used in building material (e.g., for the construction, interior applications, and the furniture industry) (Liu, 2018; Papadopoulou, 2016;

Lubis M. A., 2018). Urea formaldehyde is an integral part of product design; according to the literature, it can account for 8–10 percent by weight of the wood panel (Liu, 2018).

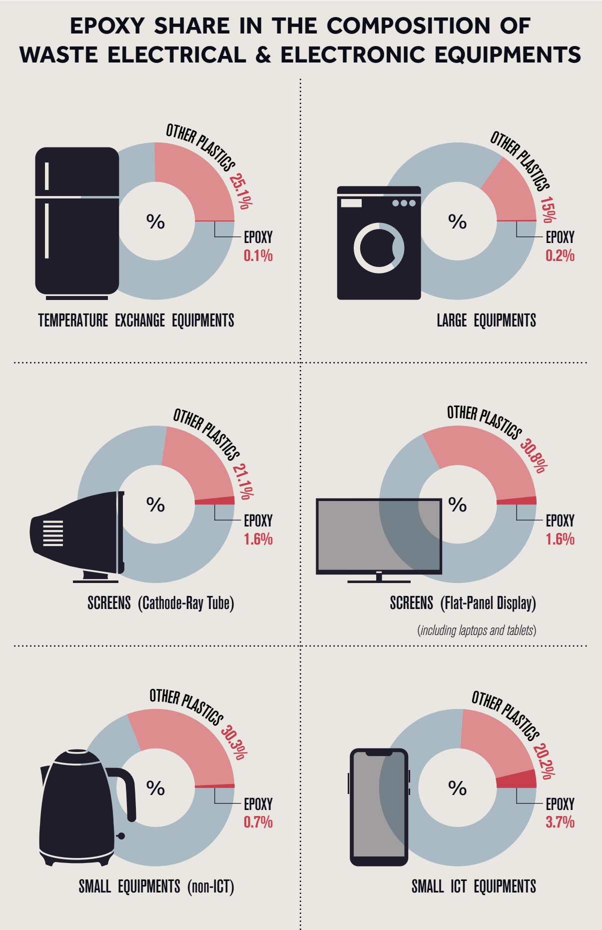
Phenol formaldehyde (PF) is made by reacting phenol with formaldehyde in the presence of base-catalyst (resoles) or using an acid catalyst (novolacs). These resins are heat resistant and have low thermal conductivity and are therefore used in automotive parts and insulation materials (Markets and Markets, 2021). Nearly half of the phenol formaldehyde resins produced are used in plywood adhesive applications (Rogers & Long, 2003). They are also used as glues and adhesives in the paint and varnish, decorative laminate, rubber, aircraft, aerospace, boating, shoe, artificial nail, leather, and electronic industries (Dickel, 2002; Nagashima, 2003; Saleem et.al., 2016). These resins are used in coatings in food packaging (e.g., in coating for interiors of food and beverage cans) and in manufacturing of protective coatings used for tank, drum, and pipe linings.

Melamine formaldehyde is made by condensation of melamine and formaldehyde. Initially, melamine formaldehyde resins were used as wood adhesives, but today, they are also used in ornamental laminate flooring, varnish, compounds, fire-resistant coatings, and water-resistant coatings. Melamine formaldehyde resins are mostly used in the binding and lamination industries, which account for 49% and 30% of total output, respectively (Ullah et.al., 2015). They can also be applied to alter the characteristics of paper and cellulosic fabrics (Ullah et.al., 2015; Park, 2010; Raval, 2006; Kumar, 1990). Additionally, these resins are used in a variety of food contact products, such as dishes and kitchen equipment (Ebner, 2020). Melamine formaldehyde resins are clear and transparent and therefore used more in decorative applications than phenol formaldehyde resins (Britannica, 2025).

Alkyd resins are primarily used as coating materials in the paint industry (Yun et.al., 2020). It is estimated that alkyd resins account for about 70% of the conventional binders used in surface coating applications (Chardon, 2021) and are the most broadly used types of coatings globally (Research Cosmos, 2018). These coatings are modified to meet a wide range of requirements through the addition of reagents or modifiers.

Epoxy resins comprise a significant segment of the commercial thermosets market, with most of them derived from fossil fuel-based bisphenol A (BPA) (Zhou et.al., 2019). Epoxy resins are used across many industries such as automotive, aerospace, electrical and electronic equipment, transportation, wind turbines, construction, and sporting goods (Jin, 2015; Nguyen, 2017; Shen et.al., 2019). Approximately 40% of epoxy is used in paint and coating for heavy-duty applications (Gantrade, 2025). For instance, epoxy provides protection against UV radiation, saltwater, and other corrosive factors for windmill blades. Additionally, the automotive, marine, and aerospace industries use epoxy resin coatings as primers for corrosion protection (Mordor Intelligence, 2021). The electrical and electronic sector accounts for approximately 12% of epoxy use (Gantrade, 2025). An overview of epoxy content in electrical and electronic waste is provided in Figure 2.

Carbon fibre reinforced epoxy composites are used in the manufacturing of load-carrying lightweight structures (Ou, 2019; Seyyed Monfared Zanjani et.al., 2018; Dong, 2017), and epoxy powder coatings are used in washing machines, dryers, steel pipes and fittings used in the oil and gas industry, water transmission pipelines, and concrete reinforcing rebar.



Source: Haarman & et al. (2020) Study on the Impacts of Brominated Flame Retardants on the Recycling of WEEE plastics in Europe.

Figure 2: Electrical & electronic equipment waste

CONDENSATION PRODUCTS

Condensation products are plastics formed by the removal of water or alcohol during polymerization (Basel Convention, 2023).

Two types of condensation products, polyamides and unsaturated polyester resins, are discussed in this report. Condensation products are used in sectors such as automotive, transportation, marine, chemical, and textiles. The production of condensation products is a multi-billion-dollar market and is projected to increase in coming years (Markets and Markets, 2024).

Polyamides have properties such as chemical resistance and thermal stability and are therefore used in sectors such as packaging, electrical, construction, automotive, and textiles (Salas et.al., 2020; Datta, 2018). Most commercial polyamide, also known as nylon, production consists of polyamide 6 and polyamide 6.6, where the numbers indicate their molecular structure (Chavarria, 2004). Polyamide fibres are integrated in textiles, toothbrushes, ropes, technical components of cars, and gears (da Silva, 2020). Polyamide is used instead of metals in the automobile industry for reducing vehicle weight (Markets and Markets, 2023a).

Unsaturated polyester resins are used, for example, in glass fibre reinforced polymer, coatings, adhesives, clear casting, buttons, body fillers, work surfaces, road drainage, cladding panels, sheeting, roofing tiles, pipes, and bathroom furniture (e.g, baths and shower trays). They are also used in filled plastic products, such as sanitary ware, tanks, pipes, and gratings. They are also utilized in boat hulls and decks, closure and body panels, fenders, and the transportation industry (Allied Market Research, 2021).

FLUORINATED POLYMERS

Fluorinated polymers are a category of per- and polyfluoroalkyl substances (PFAS) that can be either thermoplastic or thermosets (see Figure 3).

There are different types of fluorinated polymers, typically divided into the following subgroups (Buck, 2011).

- Fluoropolymers are solid materials that consist of a carbon-backbone with fluorine atoms bound to the carbon atoms (Wiley, 2016). These can be either thermosets or thermoplastics. Fluoropolymers are typically solid plastic materials.
- Side-chain fluorinated polymers have polyfluoroalkyl sidechains attached to a non-fluorinated carbon backbone. They are used as dispersions applied as surfactants and surface protection (Buck, 2011).
- Perfluoropolyethers are liquids that consist of an ether (carbon and oxygen) backbone with fluorine bound to the carbon atoms. They are typically used as lubricants and oils (Hoshino, 2016).

This report covers only fluoropolymers, since it is the only solid material of the three types of fluorinated polymers.

There are different types of fluoropolymers, each used for different purposes depending on their physicochemical properties, such as heat resistance and whether they can be melted or moulded. This, in turn, depends on whether their hydrocarbon backbones are fully fluorinated or contain additional elements such as chlorine or bromine.

Fluoropolymers are employed in a wide range of commercial and industrial applications, including consumer goods and the chemical, electronic, and automotive industries (Dams & Hintzer, 2016). Fluoropolymers can also be added to other types of plastic to provide wear and abrasion resistance, lower friction, and create non-stick surfaces (Ebnesajjad & Morgan, 2019).

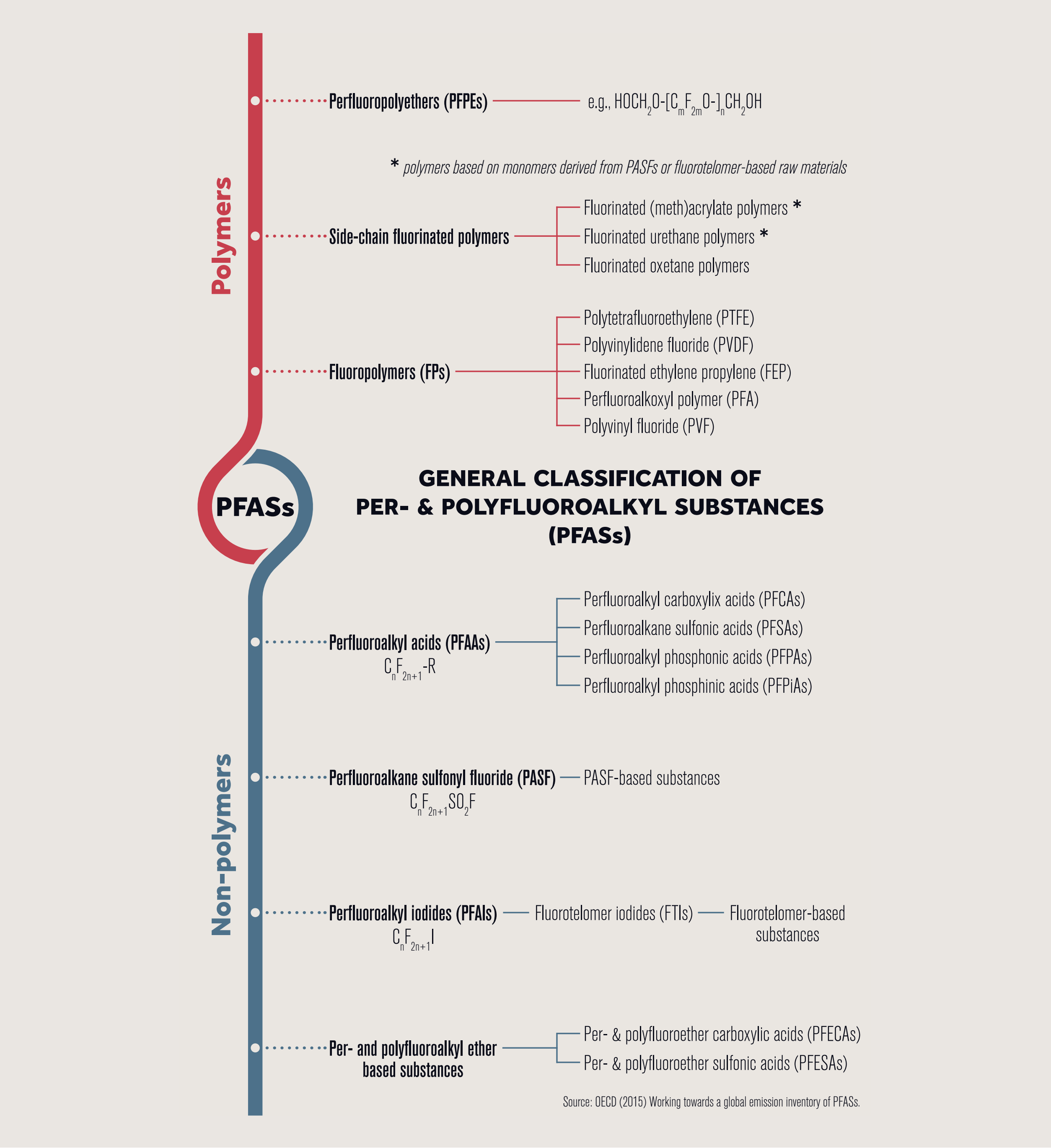
Perfluorinated polymers

Perfluorinated polymers only contain fluorine in their hydrocarbon backbones and include polymer types such as polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), and perfluoroalkoxy alkanes (PFA and MFA). The high fluorine content in perfluorinated polymers increases their resistance to heat, flame, UV radiation, and solvents (Ebnesajjad & Khaladkar, 2018a).

Polytetrafluoroethylene (PTFE) is the most frequently produced and utilized fluoropolymer (Wiley, 2015; OECD, 2021). Polytetrafluoroethylene is utilized under extreme chemical and heat conditions in chemical processes such as those in reactor vessels, storage tanks, valves, and pump fittings. It is also utilized in numerous consumer goods, including lubricants, waterproof textiles, non-stick cookware coatings, and carpet stain protection. It should be noted that polytetrafluoroethylene was not included in the exemption under the Basel Convention, and transboundary movement of all polytetrafluoroethylene waste is required to follow the Prior Informed Consent procedure.

Perfluoroethylene/propylene (FEP) is used to line cable insulation, valves, and pipes that come into contact with corrosive substances.

Tetrafluoroethylene/perfluoroalkyl vinyl ether (PFA) and tetrafluoroethylene/perfluoromethyl vinyl ether (MFA) are frequently used in the chemical processing industry as corrosion-resistant lining for vessels as well as piping and fittings for aggressive chemicals. They are also used in plastic labware.



Source: OECD (2015) Working towards a global emission inventory of PFASs.

Figure 3: General classification of per- and polyfluoroalkyl substances (PFAS)

Partially fluorinated polymers

Partially fluorinated polymers contain additional elements such as chlorine in addition to fluorine in their hydrocarbon backbones. The most common types are polyvinylfluoride (PVF) and polyvinylidenefluoride (PVDF).

Polyvinylfluoride (PVF) is produced as a film that may be bonded to metal, wood, paper, plastic, rubber, and other materials. It is used to coat things like metal surfaces, wall coverings, residential and commercial roofing, and the interiors of aircraft. Similarly, polyvinylidenefluoride (PVDF) is used, among others, as insulation for pipelines, fittings, and electrical wires. It is also one of the fluoropolymers that is utilized mostly in lithium-ion batteries.

PRODUCTION AND SALES PROJECTIONS

CURED RESINS

In 2025, 15.34 million tons of urea formaldehyde resins are projected to be produced worldwide (Mordor Intelligence, 2024). China is the world's largest producer of urea formaldehyde resins (Report Linker, 2020). It is anticipated that the global market for urea formaldehyde resins will expand at a compound annual growth rate (CAGR) of 5.23% from 2020 to 2027 (Industry Research, 2021). This growth is attributed to construction activities and the rising demand for building materials.

The precise production and consumption of phenol formaldehyde resins is unknown but was estimated to be 6 million tons per year in 2013 (Pilato, 2013). Sectors such as the construction, automotive, electric, and electronic sectors account for most of the phenol formaldehyde resin market, which was estimated at US$ 11.7 billion in 2021 (Markets and Markets, 2021). By 2024, Asia-Pacific was anticipated to have the fastest-growing phenol formaldehyde resin market, accounting for 38% of the global market (Ameri Research Inc., 2017). The output of phenol formaldehyde resins for the woodworking industry in the Russian Federation increased by 55% between 2011 and 2021 (Pervova, 2021). The size of the global plywood market was approximately US$ 91 billion in 2024 and is projected to expand to US$ 163 billion by 2034, driving up demand for phenol formaldehyde resins (Precedence Research, 2024).

The melamine formaldehyde resin market is also expected to grow significantly, increasing from US$ 722.5 million in 2024 to an estimated US$ 1.36 billion by 2034, driven primarily by rising demand in the building, laminated furniture, and automotive sectors (Fact.MR, 2025).

The alkyd resin market is anticipated to grow from approximately US$ 5 billion in 2024 to US$ 6 billion by 2030, although estimates may vary between sources (Research and Markets, 2025). The demand for alkyd resins is mainly boosted by the growth in the construction and automotive industries, the rise in urbanization, and more investments in infrastructure. Alkyd resins in primary form account for 0.0045% of global trade (OEC, 2025b).

The demand for epoxy in various sectors such as the automotive, construction, electrical and electronics industries along with advancements in technology are expected to drive the epoxy market from approximately US$ 13 billion in 2023 to US$ 17 billion by 2028, although estimates may vary between sources (Markets and Markets, 2023b). Epoxide resins account for 0.036% of global trade (OEC, 2025a).

CONDENSATION PRODUCTS

In 2023, the polyamide market was valued at approximately US$ 44 billion, and by 2028, it is expected to reach US$ 56 billion, making it one of the fastest-growing markets (Mordor Intelligence, 2025). The market for polyamide 6 is expected to reach US$ 13 billion by 2029, with Asia-Pacific leading with approximately 41% market share in 2020 (Industry Arch, 2019). Through 2027, Asia-Pacific is expected to use a significant portion of polyamide resins due to rising demand in the chemical and automotive industries, particularly in India and China (Global Market Research, 2021). In 2022, polyamides in primary forms accounted for 0.078% of global trade (OEC, 2025c).

The market for unsaturated polyester resins is anticipated to expand from approximately US$ 10 billion in 2021 to approximately US$ 13 billion by 2026 (Research and Markets, 2021). In 2022, unsaturated polyesters in primary form accounted for 0.016% of global trade (OEC, 2025d).

FLUOROPOLYMERS

The largest end-use application for fluoropolymers is in the automotive and transportation sectors. Fluorinated polymer usage was recently estimated to have climbed by 19% between 2015 and 2018 to reach 320 million tonnes globally (EEA, 2021). The revenue from the global fluoropolymer market was anticipated to exceed US$ 8 billion in 2024 and is projected to grow to US$ 13 billion by 2032, with Asia-Pacific expected to have the fastest growth (Fortune Business Insights, 2024).

POST-INDUSTRIAL AND POST-CONSUMER PLASTIC WASTE MANAGEMENT

OVERVIEW OF RECYCLING

Plastic waste can be divided into two categories: post-consumer waste that is generated at the end of life of plastic products in household or commercial use and post-industrial (or pre-consumer) waste that is produced during manufacturing processes (Huysman, 2017).

Even though some recycling technologies may be applicable to both post-consumer and post-industrial waste, one major difference is the need for collection and sorting of post-consumer waste. The collection and sorting of post-consumer waste is a key challenge to meeting the Basel Convention plastic waste exemption requirement of waste being “almost free from contamination and other types of wastes”.

When assessing whether a product is truly recyclable or not (also known as the recyclability of the product), many factors need to be considered. These include whether it was made from plastic waste and, when disposed of, if it will be used in the production of new products with equivalent properties. Other considerations include if a product, when it becomes waste, is collected, sorted, and aggregated into defined streams and processed (RecyClass 2025).

Closed-loop recycling, which involves reprocessing material into new product applications with equivalent properties, differs from open-loop recycling. An example of open-loop recycling is textile waste being repurposed in other sectors such as construction or agriculture. The recyclability of different plastics depends on several factors, including whether the polymer is a thermoplastic or thermoset, the presence of chemical additives, and whether a product is made from one polymer or from composite materials.

Thermoset plastics cannot be re-melted and re-moulded and are therefore hard to recycle, so most recycled plastics are thermoplastics. The presence of intentionally or unintentionally added hazardous chemicals can be an obstacle for introducing a safe recycled product on the market. Composite materials also require separate processes for each of their different parts, which adds complexity and cost to the recycling process. However, in most cases, plastics become an integral part of the product design with limited possibility to be segregated.

Mechanical recycling is the method used for plastic recycling in most countries. It involves physical sorting, size reduction (e.g., flaking and shredding), cleaning and drying, thermal melt-extrusion and pelletizing, and compounding of waste plastic. Mechanical recycling is mostly limited to thermoplastics, which melt when heated and harden when cooled down. Some thermoplastics such as polytetrafluoroethylene cannot be remelted but only softens when heated, making mechanical recycling challenging. Instead, polytetrafluoroethylene waste is ground into fine powder and added to other products (EEA, 2021).

Chemical conversion (also called chemical recycling) is an umbrella term for processes where the plastic polymer molecules are broken down into monomers or oligomers processed and used as base chemicals (Basel Convention, 2023). Three main types of chemical conversion processes are typically included: solvent purification, chemical depolymerization and thermal depolymerization. There are no internationally agreed upon guidelines on waste undergoing the chemical conversion processes. In addition, chemical conversion, by its nature, is not recycling.

The Basel Convention declined to include chemical conversion in its technical guidelines on plastic waste management in 2023 on the basis that it could not be demonstrated to be Environmentally Sound Management (ESM) of plastic waste. A lifecycle study by U.S. government researchers found that technologies proposed for chemical conversion have economic and environmental impacts 10 to 100 times higher than virgin polymer production due to high energy requirements, subsequent need for upgrading, and low yield of suitable monomers (Uekert et al., 2023). The principle of chemical conversion is to separate target monomers or polymers from contaminants such as intentional and unintentional additives. This process results in significant hazardous waste streams composed of rejected materials which increase costs and cause operational difficulties. Pyrolysis – thermal depolymerization – is affected by additives, heteroatoms, soil, and other resins, leading to challenges in both operation and product quality (Buekens, 2006). With solvolysis, a type of chemical depolymerization, other problems include the prohibitive cost of different solvents and anti-solvents (one for each plastic type), the significant quantities of solvent waste generated, and the effort needed to separate the solvents from plastic additives (Vogt et al., 2021).

Finally, energy recovery refers to the incineration of waste, including plastics, which extracts energy from combustion. The effectiveness of energy recovery largely depends on the method used, which is linked to advanced technologies designed to prevent emissions of harmful substances as well as overall waste management practices. Countries with limited household waste sorting practices will produce waste with a high moisture content and potentially waste containing hazardous materials in waste intended for incineration. A recent review on solid waste management strategies linked to energy recovery in developing countries found several challenges and shortcomings linked to overall waste management practices (Khan et al., 2022).

The following section assesses the currently available recycling techniques for cured resins, condensation products, and fluoropolymers to determine the possibility of recycling these materials. Waste management options discussed in this section apply to both post-consumer waste, which includes composite consumer items, and post-industrial wastes derived from manufacturing processes.

RECYCLABILITY OF CURED RESINS

Cured resins are thermoset polymers and therefore cannot be remelted, making recycling difficult (Basel Convention, 2023). The current waste management of cured resins is summarized in Figure 4.

Chemical conversion has been suggested as an option for cured resins but has only been shown at the research level (Godinho et al., 2021; Ren, 2021; Lubis, 2018; Liu, 2018). In addition, chemical conversion can only be done in specific conditions, which makes recovery costs high for large-scale recovery (Godinho et al., 2021).

Cured resins are instead reused as particle additives or fillers in other products after size reduction through crushing, cutting, grinding, extrusion, and other processes (Yang et.al., 2019). In this process, waste fibres are cut into shorter fibres or ground into a fine powder for secondary use. In most cases, the recycled fibres obtained are characterized by low performance, reduced physical properties, and an unstructured, rough, and inconsistent composition with very limited reuse potential. As a result, they can only be used in low-value applications.

Epoxy resins are difficult to manage at their end-of-life (Huang et al., 2025). However, literature reports find that they are sometimes used in low-value applications, such as fillings in paints or building components (Ribeiro et al., 2015; Moeser, 2014).

The manufacturing processes during which melamine formaldehyde resins are integrated in products such as heat or sound insulation materials generate large amounts of leftover melamine formaldehyde resins. These melamine formaldehyde resins leftovers are used as aggregate in light concrete (Srichaiyo et al., 2018) or as a flame-retardant filler in polyurethane foam (Wang et.al, 2019). Reuse of waste containing melamine formaldehyde resins generated during manufacturing processes of melamine formaldehyde-impregnated paper has been used in powder form as a binder for particleboard or other wood panels (Fur, 2004).

Cured resins are an integral part of a variety of consumer products, such as plywood, particleboards, and fibreboards, and their removal is considered a major challenge. It is important to note that the removal of adhesives in these products would only be for the purpose of recycling waste wood panels – not for recycling the cured resin polymers. Even recycling fibreboard waste for manufacturing new panels is a difficult task, as the copious amounts of adhesives have inherent infusibility and insolubility.

Scientists are working to find appropriate polymer structures and suitable techniques that could be more favourable for wood-based product recycling, but this work is still at the research stage (Nuryawan et al., 2020; Liu, 2018). Even if wood products with cured resins can be recycled, for example, if urea formaldehyde resins are removed from products, the hydrolyzed solutions created would contain formaldehyde and other chemicals, creating a new waste stream that would require further treatment to avoid pollution (Liu, 2018).

Considering the limitations of recycling cured resins and associated materials, the common practice for disposal of waste containing these polymers is combustion or landfill (Fink, 2018). Combustion of plastics such as cured resins emits pollutants and produces burning residues. For example, combustion of urea formaldehyde resins releases nitrogen-containing gases, including ammonia (NH3), hydrogen cyanide (HCN), isocyanate (HNCO), and nitrogen oxides (NOx) (Girods et al., 2008b; Girods et al., 2008c), and the burning residues contain heavy metals.

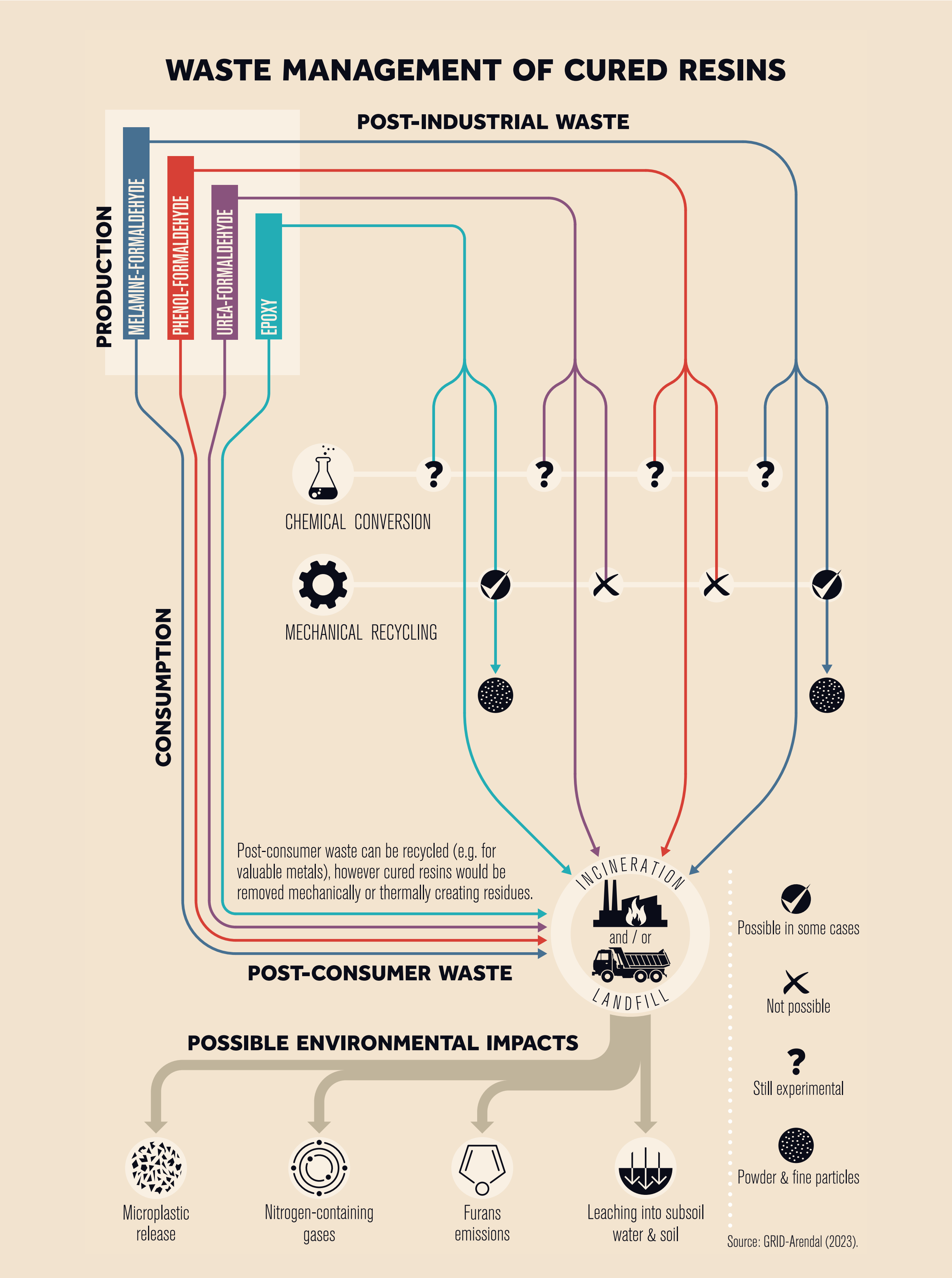


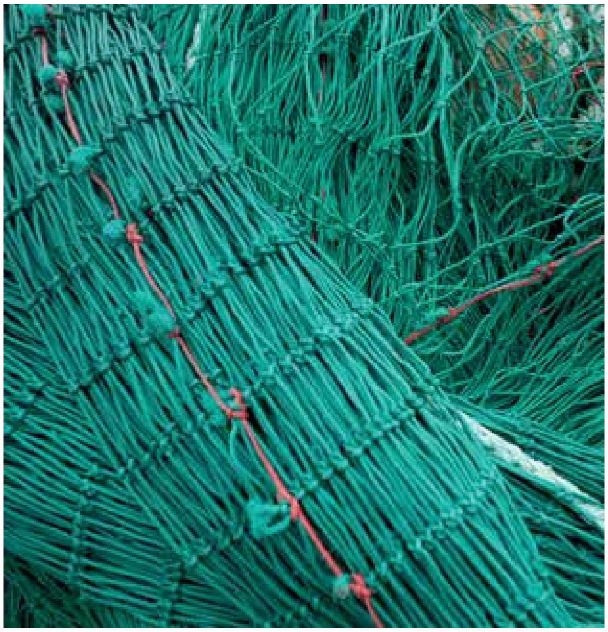
Figure 4: Waste management of cured resins

RECYCLABILITY OF CONDENSATION PRODUCTS

Polyamides can be thermoplastics or thermosets depending on their type. For instance, polyamide 6 is a semi-crystalline thermoplastic that dominates usage within the polyamide family (Kunchimon, 2019). By contrast, unsaturated polyesters are thermosets. The current waste management of condensation products is summarized in Figure 5.

Multiple efforts are being made to manage polyamide waste in open-loop and closed-loop processes. Mechanical polymer recycling by melt-extrusion is used for pure nylon (Ribul, 2021; Kunchimon, 2019). The advantage is that this thermomechanical recycling process, where synthetic fibres are melted before being re-spun into new fabrics, can also be used for mixtures of pure synthetic polymers. However, the challenge with melt-extrusion technology is that the properties of re-spun elastane fibre break down unless they are transformed into solid shapes such as bars (Ribul et.al., 2021).

Polyamide is commonly used for fishing gear; however, the design of fishing equipment is more complex. The majority of fishing nets also contain low- and high-density polyehylene, polyethylene terephthalate, and polypropylene (Sala & Richardson, 2023). They are reportedly recycled through mechanical processes, where polymer waste is reprocessed into a product with properties equivalent to the original product or a lower quality product (Sala & Richardson, 2023). Some fractions of fishing gear cannot be recycled (Sala & Richardson, 2023).



Plastic fishing nets

There is also a challenge in post-consumer waste where polyamides are an integral part of composite consumer products, such as textile waste, resulting in less than 1% of textile waste being recycled through mechanical recycling (Juanga-Labayen et.al., 2022). Multi-component textiles limit recycling potential, and technologies to recycle certain blended fabrics, including synthetics, animal, and natural fibres, are yet to be developed.

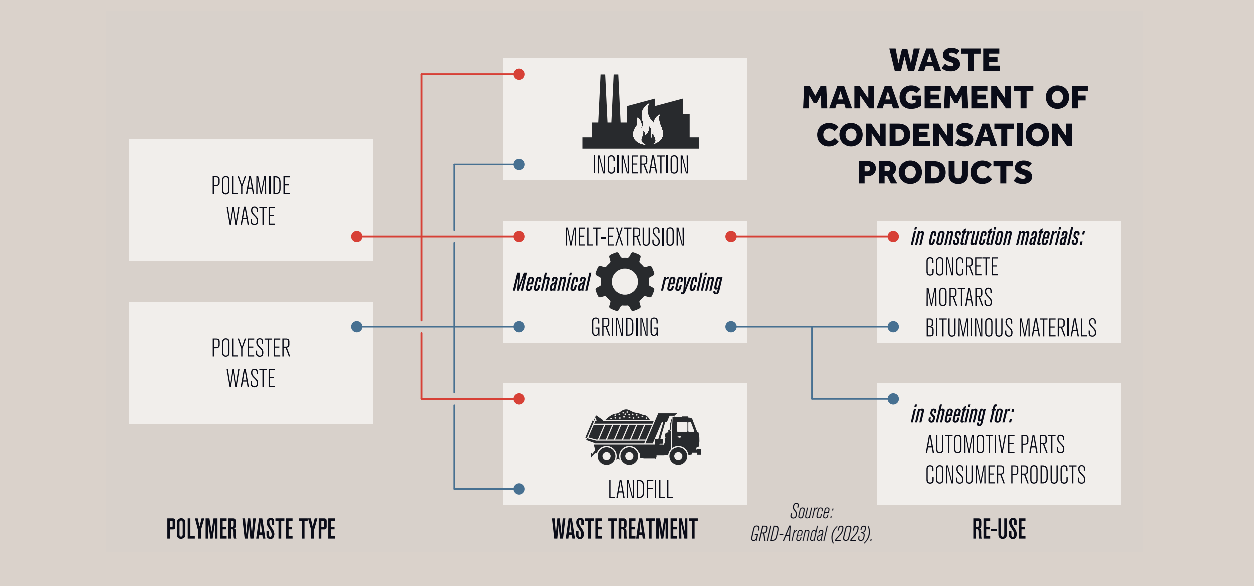
The open-loop process repurposes textile waste materials for use in other sectors, such as construction, agriculture, and gardening. Repurposing material is an open-loop waste management option that, in other words, transfers waste into a different form. For instance, the polyamide powder resulting from the mechanical recycling of the waste is repurposed for use in building materials such as recycled mortars (Salas et. al., 2016; Gadea, 2013; Horgnies, 2014). However, this postpones final disposal.

Besides mechanical recycling, other methods for managing textile waste exist, though their large-scale implementation has not been demonstrated. Chemical conversion, also known as chemical recycling, breaks down plastic waste into its monomers or oligomers through depolymerization. In small-scale experiments, this has been shown as a method that can potentially be used for synthetic fibres like polyamids and different types of fibre blends. However, as discussed earlier, it is complex, costly, creates large hazardous waste streams, and has not been proven to be environmentally sound.

As thermosetting polymers, unsaturated polyester resins and its composites, such as glass fibre reinforced unsaturated polyester, can be repurposed using mechanical techniques, where they are ground into a powder for use as fillers or as a partial reinforcement in new composite materials. This process is energy intensive and drastically reduces the length of recovered glass fibres, which limits its capacity for reuse (García, 2014). Pulverized polyester waste can be used in blends with the original or other materials as fillers in construction materials like concrete (Zegardło et.al., 2018; Sabău et.al., 2020), mortars (Farinha, 2019; Rodin et.al., 2018), bituminous materials for pavements (Rahman, 2020), and in sheeting for the production of automotive parts and other consumer products (Yoon et.al., 1997; Saricam & Okur, 2018).

RECYCLABILITY OF FLUOROPOLYMERS

Fluoropolymer synthesis and production results in the generation of waste that can sometimes be gathered and recycled (Dams & Hintzer, 2016). This includes production polymers that do not fulfil technical and quality



Source: GRID-Arendal (2023).

Figure 5: Waste management of condensation products

requirements and cannot be used for the applications for which they were designed (Ebnesajjad & Khaladkar, 2018b; Drobny, 2017). The current waste management of fluoropolymers is summarized in Figure 6.

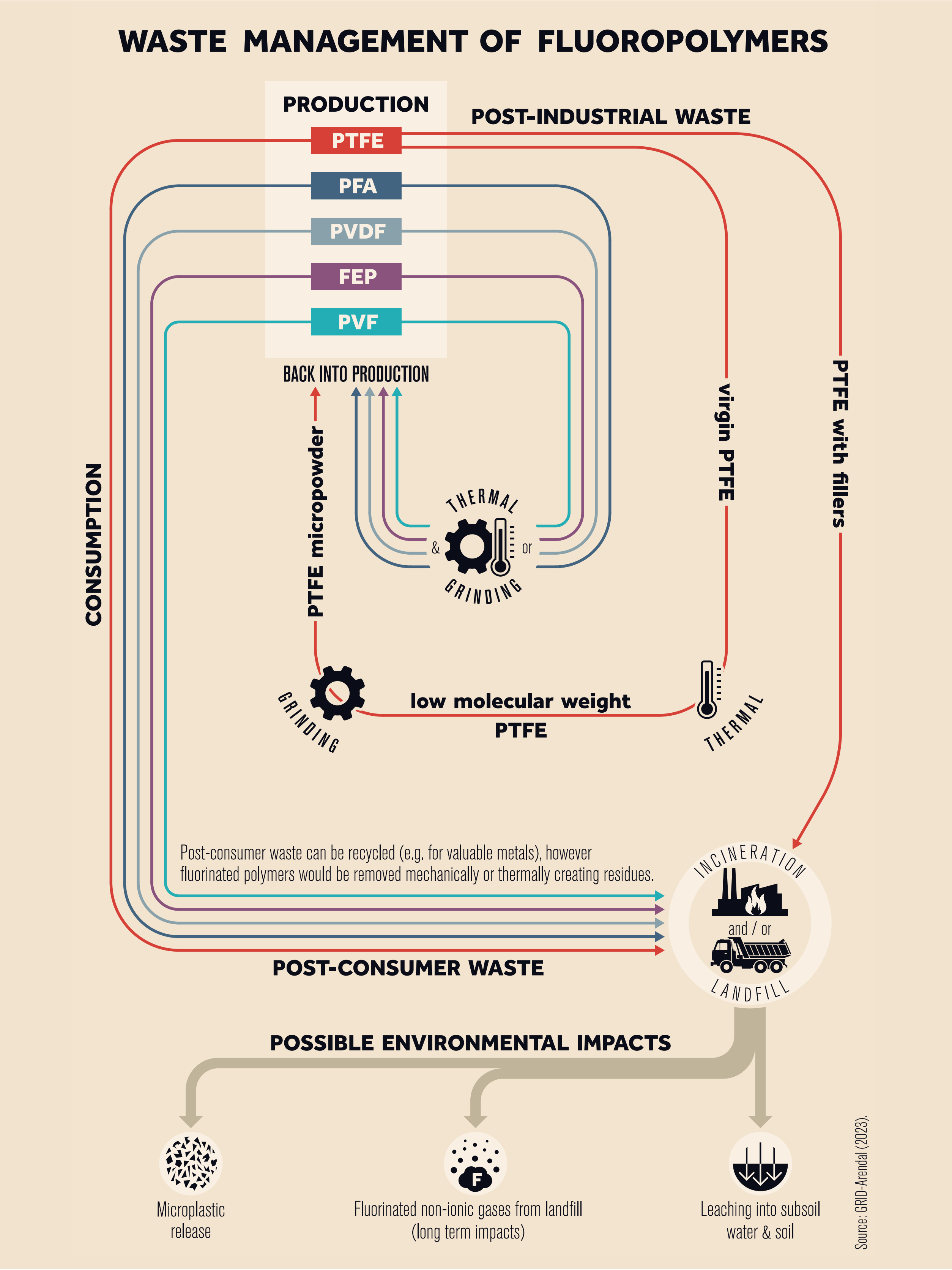
Thermoplastic fluoropolymers such as polyvinyl fluoride (PVF), fluorinated ethylene propylene (FEP), polyvinylidenefluoride (PVDF), and perfluoroalkoxy alkanes (PFA) can be mechanically recycled through grinding, melting, and extrusion (Drobny, 2017; Ebnesajjad & Khaladkar, 2018b; Wahlström et al, 2021; AlMaadeed, 2020).

The manufacturing of unfilled polytetrafluoroethylene (PTFE) results in small amounts of scrap material from wet waste materials and off-specification materials (Dams & Hintzer, 2016). Similar to the thermosets described above, these sometimes undergo size-reduction, and the resulting powder is used in other applications. Thermal or high-energy radiation can be used to degrade unfilled polytetrafluoroethylene into low molecular weight polytetrafluoroethylene, which is further milled into polytetrafluoroethylene powders as small as a few microns. This polytetrafluoroethylene powder is added to plastics, inks, oils, lubricants, and coatings to introduce fluoropolymer-like properties such as reduced wear rates and friction (Dams & Hintzer, 2016; Drobny, 2017; Wahlström et al, 2021). Additionally, sintered polytetrafluoroethylenes, which have been treated at temperatures above their melting point, can be ground into particles (moulding powders) and reused in a few less demanding applications (Dams & Hintzer, 2016; Drobny, 2017; Ebnesajjad, 2015; Wahlström et al, 2021).

The common mechanical recycling techniques do not apply to filled polytetrafluoroethylene compounds, which are difficult to melt. In addition, recycled polytetrafluoroethylene does not combine easily with virgin polytetrafluoroethylene material (Drobny, 2017). Furthermore, fillers such as glass fibres, charcoal, graphite, bronze, and molybdenum sulphide can make up to 40% of the volume of the filled polytetrafluoroethylene (Wiley, 2016), thus making it unsuitable for typical mechanical recycling. As a result, there are no recognized large-scale techniques for recycling filled polytetrafluoroethylene (Dams & Hintzer, 2016).

In general, a large portion of used fluoropolymers in post-consumer waste is disposed of in landfills, incineration facilities, or blast furnaces. Due to the strong corrosiveness of the hydrofluoric acid produced during the process, communal waste incinerators can only accept very small levels of fluoropolymers.

Similarly, fluoropolymer-containing products are often either open-burned, incinerated, or landfilled at their end-of-life (Dams & Hintzer, 2016; Stoiber et.al., 2020; Wiley, 2016). Fluoropolymers are integrated into a variety of products that make it nearly impossible to recycle them after use. They often make up a minor, integral element of a product, making it unfeasible to separate, clean, and reclaim the fluoropolymers utilized (Dams & Hintzer, 2016; Wiley, 2016; Plastics Europe, 2021). Additionally, fillers and colours added to fluoropolymers can make recycling challenging, impossible, or dangerous depending on their nature (Dams & Hintzer, 2016; Ebnesajjad & Khaladkar, 2018b).



Source: GRID-Arendal (2023).

Figure 6: Waste management of fluoropolymers

CONCLUSION AND POLICY RECOMMENDATIONS

This report, based on the scientific literature, reveals that cured resins, condensation products, and fluorinated polymers – being integral parts of complexly designed industrial and consumer products – face challenges in being recycled in an environmentally sound manner.

Some thermoplastics, such as certain fluorinated polymers, can be recycled through grinding, melting, and extrusion, while thermoset plastics, such as cured resins and thermoset polyamides, cannot be re-melted and re-moulded, making them difficult to recycle in a closed-loop system. Some of these polymers are instead reused as particle additives or fillers in other products after size reduction through crushing, cutting, grinding, extrusion, and other processes. In an open-loop waste management system, repurposing materials transfers waste into new applications or alternative forms but ultimately limits waste management options to landfills or incineration.

The limited recycling options for cured resins, condensation products, and fluorinated polymers need to be considered – especially given the increased demand for these polymers in sectors linked to green technologies as well as the shift to lighter materials in areas such as in the automotive sector. These shifts should account for the risks associated with waste management options, particularly when materials cannot be managed in an environmentally sound manner.

Plastics that cannot be produced, used, or recycled in a safe and sustainable manner should be phased out, as they are incompatible with a circular economy approach and can harm human health and the environment. This includes plastics that contain hazardous chemicals and plastics that are integral parts of products and are not feasible to extract, such as cured resins, condensation products, and fluorinated polymers.

The polluter pays principle must be adequately legislated and implemented as part of a holistic, system-based approach to plastic waste management, including the internalisation of waste management costs by producers of plastics and plastic products.

The exemptions from the Prior Informed Consent procedure required under the Basel Convention for cured resins, condensation products, and fluorinated polymers should be removed, as these exempted polymers are typically difficult to recycle in an environmentally sound manner or to keep almost free from contamination and other types of wastes.

In addition, given the hazardous properties of many of these plastics when openly burned, incinerated, or landfilled, they should be classified as hazardous waste and controlled under the Basel Ban Amendment.

Finally, the Conference of the Parties to the Basel Convention concluded in 2023 that chemical conversion has not been proven to be an environmentally sound management practice. Until independent scientific evidence demonstrates otherwise, chemical conversion should not be seen as a viable option for plastic waste.

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