PLASTIC WASTE MANAGEMENT HAZARDS

WASTE-TO-ENERGY, CHEMICAL RECYCLING, AND PLASTIC FUELS

Lee Bell
Professor Hideshige Takada

International Pellet Watch

IPEN
for a toxics-free future

PLASTIC WASTE MANAGEMENT HAZARDS

Authors
Prof. Hideshige Takada, *Dept. of Environmental & Natural Resource Sciences*
Lee Bell, *IPEN Mercury and POPs Policy Advisor*

IPEN is a network of non-governmental organizations working in more than 100 countries to reduce and eliminate the harm to human health and the environment from toxic chemicals.

www.ipen.org

International Pellet Watch is a nonprofit ecological research group whose mission is to monitor the occurrences of plastic waste, and plastic pellets in particular, around the world. Based at the University of Agriculture and Technology, Department of Environmental Resources Science in Tokyo, Japan, the group has been gathering data and educating the public about the hazards of plastic waste since 2013.

http://pelletwatch.org/

ISBN: 978-1-955400-10-7

IPEN Production Team: Bjorn Beeler, Tim Warner, Betty Wahlund

Cite this publication as:
Takada, H. and Bell, L. *Plastic Waste Management Hazards*. International Pollutants Elimination Network (IPEN), June 2021.

CONTENTS

EXECUTIVE SUMMARY

Plastic waste has become an unprecedented pollution issue around the globe. From visible plastic litter on land and in oceans to invisible microplastics in lakes, mountains, and rain, the planet is increasingly blanketed in the petrochemical remnants of plastic production. With petrochemical companies avoiding fossil fuel carbon liabilities by massively increasing plastic production, the amount of plastic waste generated is set to climb dramatically.

This report examines the current and emerging methods by which plastic waste is managed globally and questions whether any of them present a solution to the rapidly accelerating generation of plastic waste. The short answer is that recycling at the margins cannot provide a solution to plastic pollution when plastic production is set to grow exponentially. Other 'recovery' waste management techniques such as incineration, plastic to fossil fuel, and downcycling to incorporate plastic waste in roads, will simply generate more pollution. The only long-term answer to plastic pollution is to produce less plastic. This seems unlikely while the petrochemical industry needs plastic as a safe haven from its carbon liabilities. Increasing plastic production offsets falling demand for its fossil fuels.

The first section of the report considers plastics in context of a global circular economy, both as an economic commodity and a complex, often toxic, material. It questions whether plastic recycling is economically viable, environmentally sustainable, and socially just. The second section examines *chemical recycling*, which is now heavily promoted by the plastics industry as a way to eliminate plastic pollution by using chemical, thermal, and solvent depolymerization to generate feedstock and polymers to make new plastic from plastic waste. This section explains why chemical recycling will remain a fringe activity due to economic barriers, intensive energy use, and hazardous waste outputs.

The third section considers another plastic industry 'solution' of turning plastic into liquid fossil fuels and burning them, and concludes that the practice is inefficient, polluting, and uneconomical. Similarly, recovering energy from burning plastic waste in incinerators and cement kilns as 'alternate fuels' or 'refuse-derived fuels' results in toxic emissions, toxic ash, high intensity carbon releases, and wastes resources, entrenching a linear economy.

Section four assesses mechanical recycling, examines its limitations, and discusses key barriers to its expansion. Key challenges to effective mechanical recycling of plastic waste are toxic chemical additives introduced during the production of virgin plastics, inability to recycle mixed polymers into mono-polymer production streams, competition with cheap virgin plastics, and complex packaging made from mixed materials—plastics, metals, and paper—that are technically difficult and expensive to separate and recapture. While mechanical recycling could do a lot more if industrial design of plastic improved and poorly designed plastics, as well as their toxic additives, were eliminated from the market, it suffers limitations that prevent it from becoming a solution to plastic waste.

Sections five and six address some of the most toxic of plastics—those that are contaminated through production, recycling, or aquatic exposure with persistent organic pollutants (POPs), the most toxic, persistent and bio-accumulative chemicals ever produced. These sections provide information on how the plastics become POPs-contaminated, how to manage them, and what techniques and technologies are available to destroy them in accordance with the Stockholm Convention's requirements. Sound management options for medical plastic wastes are also explored. Finally, this report briefly examines the issues associated with incineration and landfill of plastic waste.

It is apparent that neither chemical nor mechanical recycling of plastic waste can provide solutions to the rapidly increasing crisis of plastic pollution driven by exponential plastic production. The only viable solution is to cut plastic production, use alternative materials, and ban non-essential uses of plastic.

KEY FINDINGS

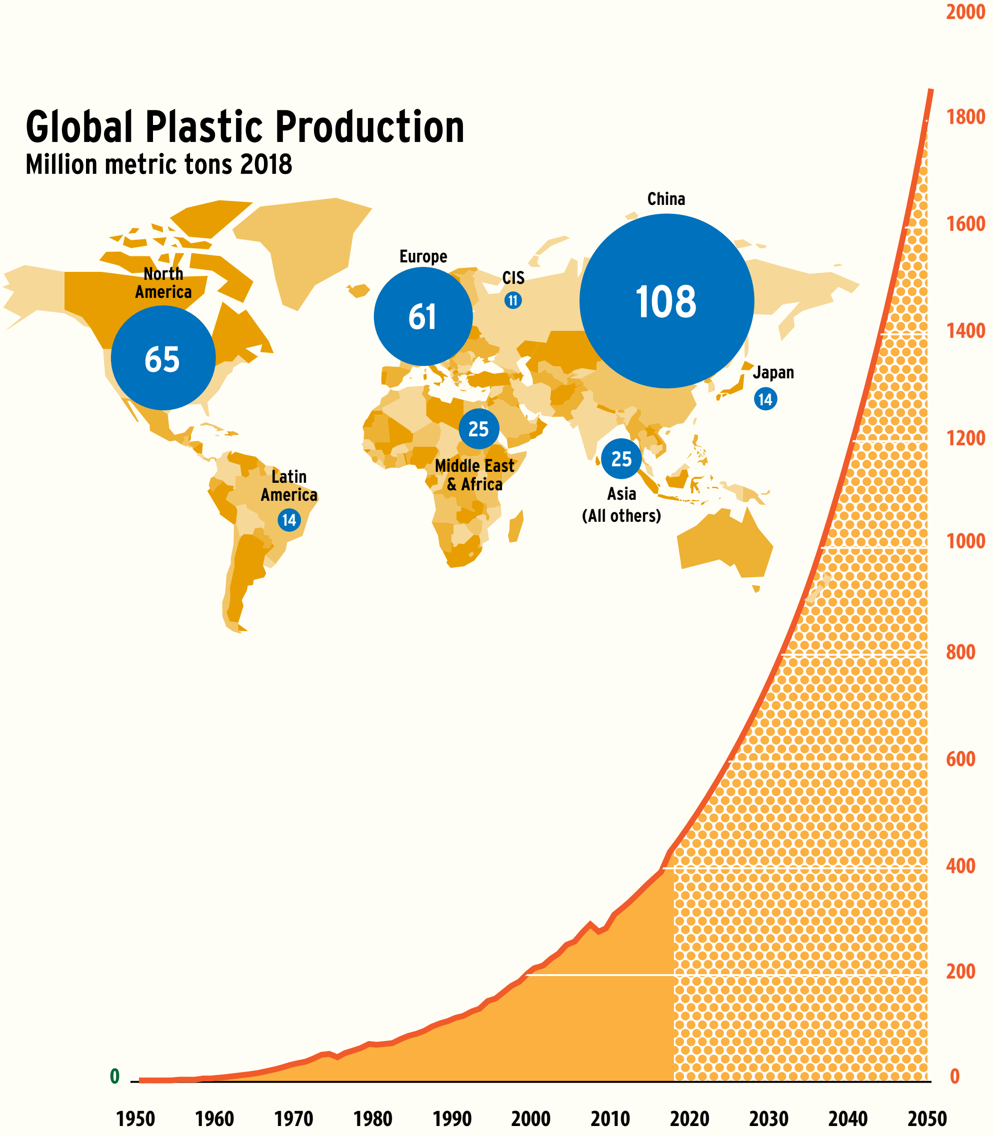
- Neither mechanical nor chemical recycling have the capacity or potential to reduce plastic pollution of the environment unless plastic production is regulated and minimized.
- Following current trends, 1 800 million tonnes of plastic will be produced and 900 million tonnes of plastic will be incinerated globally in 2050.
- Without changes in current practices 108 million tonnes of plastic waste will be landfilled, dumped, or openly burned in 2050, and mainly in low-income countries.
- Toxic chemical additives are a major ‘invisible’ aspect of environmental plastic pollution and humans are exposed at increasing rates as production and recycling increases.

- Toxic chemical additives are barriers to mechanical recycling and will become high-volume hazardous waste residues from chemical recycling.
- Additives include endocrine-disrupting chemicals (EDCs), persistent organic pollutants (POPs) and heavy metals that migrate from plastic during production, use and disposal phases.
- Chemical depolymerization of plastics by pyrolysis and gasification (chemical recycling) requires very high-energy input, has high Global Warming Potential and has high potential to create toxic exposures to workers and a hazardous waste residue stream.
- Chemical depolymerization by pyrolysis and gasification is likely to contaminate polymer-derived fuels with POPs which will be released in an uncontrolled manner.
- Solvent-based regeneration of plastics can produce clean polymers but will have a significant hazardous residual waste stream.
- Supercritical and subcritical water oxidation (SCWO) have potential as a more environmentally sound recycling technique for polymers compared to most other chemical recycling processes. SCWO is also one of the cleanest methods for destruction of POPs-contaminated plastics that cannot be recycled.
- Microplastic pollution cannot be addressed by either mechanical or chemical recycling and must be subject to production minimization.
- Chemical recycling can be used to purify monomers and polymers for reuse from some contaminated, mixed plastics more effectively than mechanical recycling, but will generate significant toxic waste streams in the process.
- Non-combustion technology must be ramped up for the management of POPs-contaminated waste and to stop the spread of POPs from incineration of plastic.
- Refuse-derived fuels (RDF) may contain hazardous substances, do not contribute to a circular economy and represent the ‘end of the line’ for the resources used this way. Burning RDF contributes to climate change and polluting emissions.

GLOSSARY

ABS	Acrylonitrile Butadiene Styrene
ASR	Automotive shredder residue
BFR	Brominated flame retardant
CFRP	Carbon fibre-reinforced plastics
CKD	Cement Kiln Dust
DMT	Dimethyl Terephthalate
DMCR	Dehalogenation by Mechanochemical Reaction
DDE	Dichlorodiphenyl-dichloroethylene
DDT	Dichlorodiphenyl-trichloroethane
DE	destruction efficiency
EDC	Endocrine-disrupting chemicals
ESM	Environmentally Sound Management
EU	European Union
FCM	Food Contact Material
FMCGC	Fast-Moving Consumer Good Companies
FT-NIR	Fourier Transform Near-Infrared
GEF	Global Environment Facility
GFRPs	glass fiber-reinforced plastics
GHG	greenhouse gas
iSCWO	Industrial supercritical water oxidation
GPCR	Gas-Phase Chemical Reduction
GWP	Global Warming Potential
HBCD	Hexabromocyclododecane
HIP	High-impact polystyrene
HDPE	High-density polyethylene
JESCO	Japan Environmental Safety Corporation
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
LPCL	Low POP Content Level
MCD	Mechano-Chemical Destruction
MEG	Monoethylene Glycol
MSW	Municipal Solid Waste
NIAS	Non-intentionally added substances
OECD	Organisation for Economic Co-operation and Development
PA	Polyamides
PAE	Polyamide-epichlorohydrin
PAH	Polycyclic Aromatic Hydrocarbons
PBDD	Polybrominated dibenzo-p-dioxins
PBDD/F	Polybrominated dibenzo-p-dioxins/furans
PBDE	Polybrominated diphenyl ether
PBDF	Polybrominated dibenzofurans
PC	Polycarbonate
PCB	Polychlorinated biphenyl
PCDD/DF	Polychlorinated dibenzo-p-dioxins and dibenzofurans
PE	Polyethylene
PEF (1)	Polyethylene Furanoate

PEF (2)	Process Engineered Fuel
PET	Polyethylene Terephthalate
PHA	Polyhydroxyalkanoates
PI	Post-industrial (plastic waste)
PLA	Polylactic Acid
PMMA	Poly(methyl methacrylate) or acrylic
POP	Persistent Organic Pollutant
POP-BFR	Persistent Organic Pollutant Brominated Flame Retardant
PP	Polypropylene
PS	Polystyrene
PTA	Purified Terephthalic Acid
PU	Polyurethane
PVC	Polyvinyl Chloride
RC	Resin Code
RDF	Refuse-Derived Fuel
TDA	Tolylenediamine
TDI	Tolylenediisocyanate
TPA	Terephthalic Acid
TRPB	Thermal Reduction Batch Processor
SCCP	Short-chained Chlorinated Paraffins
SAN	Styrene Acrylonitrile
SCWO	Supercritical Water Oxidation
SSP	Solid-state Polycondensation
UPOP	Unintentionally Produced POP
UNEP	United Nations Environment Programme
UNDP	United Nations Development Programme
VCM	Vinyl Chloride Monomer
VOCs	Volatile Organic Compounds
WEEE	Waste Electrical and Electronic Equipment
XPS	Extruded Polystyrene
XRF	X-ray Fluorescence



Global Plastic Production

Million metric tons 2018

Figure 1. Projected plastic production to 2050.

INTRODUCTION

In recent years global awareness of plastic pollution has reached nearly every level of society. Aided by the rapid spread of information through social media and information technology, everyone from schoolchildren to international lawmakers are now aware that the plastic contamination of the planet is a massive problem.

Much of this plastic contamination is visible. From the plastic bags blowing down our streets, to the marine life tangled in plastic nets and rivers choked with old plastic packaging, we are all too familiar with the sight of plastic pollution.

However, recent research indicates that this is only part of the problem and that tiny microplastics are polluting the extremities of the earth, the deepest seas (UNEP 2016, Andrady 2011, Bakir *et al.,* 2014), the highest mountains (Allen *et al.,* 2019), soil, water, every marine mammal (Nelms *et al.,* 2019), fish, and even rainfall (Wetherbee *et al.,* 2019). This combination of visible and microplastic contamination has reached critical levels that should have been addressed decades ago.

A key part of the problem is the sheer scale of existing production of plastics and limited options for end-of-life management. Global production levels for plastic were estimated at 335 million tons (Mt) in 2016 alone (PlasticsEurope 2018).

The total production of all plastic since the 1950s is estimated at 8 300 Mt, of which 6 300 Mt has become waste and 4 900 Mt has been landfilled or entered the environment (Geyer *et al.,* 2017). Much of the rest has been incinerated creating a range of persistent organic pollutants such as dioxins and furans (PCDD/DF) emissions and toxic ash (IPEN, ARNIKA, NTN 2017b).

Predictions see the 2016 production level of 335 Mt climb to a staggering 1 800 Mt by 2050 (Figure 1., Ryan 2015) as the petrochemical industry shifts its output from fuels to chemicals and plastics in a carbon-constrained market.

There has been widespread promotion of recycling, both mechanical and chemical, as a solution to the plastic waste problem but at current polymer production levels recycling is making very little impact, even in wealthy countries. When the bigger picture of massive plastic production growth and the lack of recycling infrastructure in low-income countries is considered, it becomes clear that plastic recycling is not the solution.

Addressing the plastic contamination of the planet requires a range of approaches, but three elements are critical and must be prioritized:

1. We must dramatically reduce the amount of plastic being produced – immediately.
2. We must address existing stockpiles of plastic waste (controlled, uncontrolled, and landfills) in an environmentally sound manner.
3. We must develop an environmentally sound, sustainable management system for any plastic produced in the future. This must include implementation of design, production, and end-of-life management systems that maximize polymer reuse and recycling in low-income countries as well as wealthy countries.

Put simply, we must ramp down plastic production to essential uses, deal with legacy stockpiles, and redesign plastic produced in the future to allow for environmentally sound management (ESM) within the framework of a global circular economy that does not dump plastic waste on low-income countries.

This main focus of this report is how to address existing stockpiles of plastic waste and potential methods for managing current and future end of life plastics. Reducing production of plastics is a political and regulatory issue outside the scope of this report.

1. PLASTICS IN A GLOBAL CIRCULAR ECONOMY?

A key question when considering how to manage plastic waste is whether there is a role for plastic in a global circular economy. Can it be treated like paper, glass, and metal to be recycled and reprocessed in an endless material cycle through the economy? The assessment of plastic recycling limitations in this report suggests that this may not be possible without major changes to production methods and production levels of plastic.

The concept of a circular economy where material resources are constantly cycled through a value chain of production, use, and recycling in order to maximize their utility and avoid the extraction and use of virgin materials, is a progressive antidote to a linear economy. In the classic linear economy, material resources are extracted from the environment, refined and processed into products which are used, and then become waste. As waste, they are disposed of—buried or burned and lost forever—removed from the inventory of resources that are available to produce new. Worse still, the impacts of burying or burning those resources are air, soil, and water pollution, human exposure to toxic wastes and emissions, and long-term impacts on biodiversity and climate.

Converting to a truly circular economy means that those businesses whose activities align with a circular framework will likely benefit from the changes, while those entrenched in the old linear model will find it harder and less profitable to operate. This has led to many 'linear' economic interests attempting to redefine the concept of a circular economy to include themselves as an essential element of the circular economic system. This is often seen with incineration proponents who brand the burning of wastes and especially plastic waste as 'energy recovery' or 'thermal recycling'. However, the burning of plastic waste not only generates toxic atmospheric and solid waste, it destroys the resource itself. In this case, the resources destroyed are the petrochemicals that were extracted to make the plastic and the 'embedded energy' in the plastic item. The embedded energy includes the energy to extract the oil, refine the petrochemicals, and manufacture the polymer, as well as transportation between all steps, including transport to market. All of that embedded energy is destroyed in a couple of seconds in the combustion chamber of the incinerator to extract the tiny amount of 'calorific energy' that is produced when the plastic object is combusted.

Figure 2. Linear and Circular economy.

As many industries have come to realize they belong to the old linear economy and will lose ground in a circular economy, they and their industry associations have sought to distort its definition and seek inclusion. This has led to a proliferation of definitions and interpretations of the circular economy. The Centre for European Policy Studies has identified at least 12 academic and institutional definitions (CEPS 2017) of a circular economy and a brief internet search will double that. At the core of the circular economy concept as it is broadly understood is *the avoidance of resource extraction through maximization of reuse and recycling of existing material resources and minimization of waste for the benefit of society and the environment.*

It should also be recognized that there are some things in our economy and society that we do not want to recycle, including highly toxic materials. This is recognized in the Stockholm Convention and its general prohibition on recycling POPs waste. For plastics this means that it is necessary to avoid adding toxic additives to polymers that make recycling harder, contaminate the environment, and expose workers and consumers to harm. This is almost the opposite of where plastics production is currently headed, with a booming toxic additives market, designs that prevent recycling, and exponential growth in the production of single use polymers.

The proposed industry solution of chemical recycling is largely predicated on the basis that it can separate contaminants from plastic waste, allowing near virgin quality polymers to be recovered. This does not answer the question of how to deal with all the toxic, contaminated material separated from the 'clean' polymer. It also fails to deal with the fact that those newly recycled polymers will be formulated with more toxic additives before they become products again. Conversion of plastic to liquid fuels will see the toxic contaminants shifted to the atmosphere as emissions when the fuels are burned. Depolymerization will see toxics additives removed to become a vast reservoir of hazardous sludge residue. Pyrolysis of plastic waste for hydrogen will see a rapid increase in dioxin in solid waste residues of the process, and so it goes on. The toxic waste and emissions from these processes continue to reflect a linear economic structure. Removing toxic additives from polymers would move chemical recycling closer to a circular economic reality.

Clearly some forms of chemical recycling can complement mechanical recycling to keep essential, non-toxic plastic in the circular economy. But in its current forms, it has too many elements of linear economy associated with it to lay claim to 'circularity'.

PLASTIC ACCELERATES CLIMATE CHANGE.

Every stage in the lifecycle of plastics generates significant emissions of greenhouse gasses which drive climate change and undermine the Paris Agreement. The ultimate objective of the Paris Agreement is to limit global warming to below two degrees Celsius above pre-industrial levels, aiming for 1.5 degrees Celsius, by the end of the century (Article 2). Within this framework countries must review and reset ambitious targets every 5 years (Articles 3), with a five-year system of monitoring, verification and reporting of emissions reviewed by a compliance committee. (Articles 13, 14 and 15). In addition, States should contribute funds to meet a $100 billion target by 2020 and include climate finance targets in nationally determined contributions (Article 5). The objective of the Paris Agreement is under threat from the emissions attributable to growth in plastic production and disposal.

While the focus of the Paris Agreement and most national actions has been to substitute fossil fuels such as coal, oil and gas with renewable energy, the plastics sector of the petrochemical industry has mostly avoided scrutiny. As pressure mounts on the fossil fuel industry for its carbon liabilities, its calculated shift to increased petrochemicals and plastic

Emissions from the Plastic Lifecycle

Source: © CIEL

Note: Compared to 500 megawatt coal-fired power plants operating at full capacity.

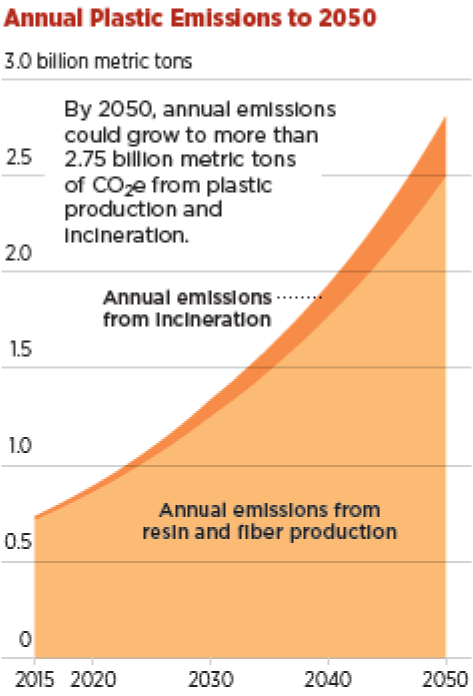
production has become a gamble to protect its increasingly beleaguered extractive assets. However, the plastic lifecycle from extraction through production to disposal has an enormous carbon footprint that threatens to grow apace with increased plastic production.

One estimate of methane releases (fugitive emissions or leaks) from the extraction of natural gas could be as high as 9% of total global production volumes (Tollefson, 2013). Methane is a potent greenhouse gas approximately 25 times more powerful than carbon dioxide over a 100-year timescale in terms of warming potential. Ethylene is a major basic chemical building block for the production of polymers. Each year more than 133 million tonnes of ethylene are produced from cracking of ethane and naphtha with high carbon emission levels. The cumulative greenhouse gas emissions for the steam cracking of naphtha and ethane amount to 1,135 and 840 kg CO_2/tonne of ethylene respectively (Ghanta *et al.,* 2014).

Incineration of plastic waste is by far the greatest CO_2 emissions source of all plastic end of life management options. Based on the energy intensive nature of pyrolysis and gasification – chemical recycling as feedstock will also generate significant net emissions. Converting plastic to fuel via these technologies will sharply increase CO_2 emissions even further as with this practice, plastics made from fossil fuels only briefly become plastic products before they are combusted as fossil fuels.

Estimates from the Centre for International Environmental Law (CIEL) indicate that in 2019, the production and incineration of plastic added more than 850 million metric tons of greenhouse gases to the atmosphere—equal to the emissions from 189 five-hundred-megawatt coal power plants (CIEL 2019).

As noted in other sections of this report, plastic production is set to rise dramatically as oil and gas corporations shift their investment from liquid fuels to polymers and petrochemicals to avoid the growing carbon liabilities associated with combusting fuel. If production growth rates increase as planned, CIEL estimate that by 2030 CO_2e (carbon dioxide equivalent) emissions[1] will rise to 1.34 gigatons[2] which is equivalent to the output of 295 new 500-megawatt coal-fired power plants (CIEL 2019). If we are to meet the Paris Agreement objective and limit global warming to 1.5°C then the amount of future carbon that can be emitted to atmosphere is strictly limited. As carbon accumulates in the atmosphere over time, the amount of carbon already released from the industrial revolution through to the present does not leave much room to add additional carbon. The remaining amount of carbon that can be added without exceeding the 1.5°C target is known as the 'carbon budget'. The current carbon budget is 420–570 gigatons of carbon and it is being rapidly depleted. By 2050 the emissions from plastic production and incineration could reach 56 gigatons of CO_2e which is equivalent to 10–13 percent of the entire remaining carbon budget.



Annual Plastic Emissions to 2050

Source: CIEL

---

[1] A carbon dioxide equivalent or CO2 equivalent, abbreviated as CO2e is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.

[2] A gigaton is equivalent to 1 billion tonnes or 1,000,000,000 metric tons.

This enormous emission source is not entirely based on the carbon emitted during the extraction and production phase of petrochemicals (although this represents the largest fraction) but is also attributable to end of life management of plastics. Incineration of plastic waste contributes significantly to overall CO_2e emissions from the plastics life cycle. Combustion of plastic packaging in waste incinerators generated 16 million metric tons of CO_2e globally in 2015 but this figure does not include the fate of an additional 32 % of plastic packaging that does not fall within a formal waste management system and is either open burned (with considerable CO_2e and toxic emissions) or lost to the environment (CIEL 2019).

Landfilling of plastic with mixed municipal waste can result in some plastic based CO_2e emissions but are magnitudes of order lower than incineration. While plastic degrades to some degree in mixed landfill due to the low pH reducing conditions, it remains largely intact. The reducing conditions accelerate the leaching of toxic additives from plastic in landfill converting additives to more toxic compounds contributing to groundwater and surface water contamination and, on balance, these environmental impacts are of far more consequence than the relatively small CO_2e emissions of plastic in landfill. The main driver of landfill emissions are organic materials generating methane – a potent GHG gas. Plastic landfilled without organic materials has very low emissions and very slow degradation rates unless it is combusted on-site. However, 'monofill' of plastics (landfill containing only plastic) is not a long -term solution to the plastic waste dilemma, but could provide an interim method of storage that minimises environmental impact in the short-term until other options are developed.

Mechanical recycling also generates CO_2e emissions due to the energy requirements of the process and transport of materials. However, if the processes and transport for mechanical recycling are based on renewable energy then emissions from this sector are extremely low. In addition, the recycling of polymers removes the emissions required to generate virgin plastic that the recycled plastics theoretically displace. As discussed elsewhere in this report, most plastics cannot be economically or technically recycled and coupled with a massive virgin plastic production expansion, recycled plastics unlikely to significantly reduce emissions from the sector.

Chemical recycling of plastic back to plastic, the proposed solution to plastic pollution of major petrochemical companies, has very high energy demands, particularly for pyrolysis and gasification which require high operating temperatures and rely on external fuel sources to maintain process heat. Most market analysis of petrochemical outputs from these processes suggest they will be directed to fuel rather than polymer production. This is due to the high price differential between virgin plastic manufactured with very low-priced petrochemicals and the high cost of chemical recycling.

If burned as liquid fuel made from chemical recycling, the entire CO_2 content of the plastic is emitted making the plastic to fuel process a very high emitter of CO_2 emissions. The carbon footprint includes energy used in collection and sorting the plastic waste, energy for heating the pyrolysis or gasification process and then burning the petrochemical output as fuel. As noted elsewhere in this report, low oil prices (the main feedstock for plastic production) and well established infrastructure for virgin plastic production can, and frequently does, reduce the price of virgin plastics to the point where recycled plastic struggles to compete on price. This tends to drive 'plastic to fuel' production from pyrolysis and gasification. Producing plastic feedstock chemicals instead of liquid fuel from plastic waste has higher costs related to purification steps, rendering the output less competitive on price than fuel outputs.

When these factors are considered, waste incineration remains the highest emission source from plastic end of life management followed by chemical recycling using pyrolysis and gasification. When the entire life cycle of plastic is assessed, it becomes clear that production of plastic must be curtailed to significantly reduce CO_2 emissions from this sector.

Despite the plastic industry investment in massive expansion of plastic production, global agreements on climate change and carbon emissions may become instruments that heavily restrict virgin plastic production by mid-century.

If global policy makers intensify their efforts in the mid-term and future carbon emissions are strictly minimised, the production of virgin plastic from crude oil could potentially be heavily restricted or halted. Crude oil consists of several fractions, i.e., gases, naphtha, kerosene, diesel oil, lubricating oil, fuel oil and residue (asphalt) fractions. Plastic is produced from the naphtha fraction of crude oil. If the fractions currently used for fuel cannot be used in the future, it may be practically and economically impossible to only extract the naphtha fraction from the earth's crust for plastic production. In the framework of the Paris Agreement, net emissions of CO_2 should be reduced to zero later this century (after 2050) which means that petroleum cannot be combusted for fuel energy after 2050. Accordingly, crude oil will be impractical and uneconomical to extract and naphtha, a fraction of crude oil, will no longer be available. Consequently, virgin petroleum-based plastics from crude oil may no longer be able to be produced after 2050.

However, plastic production via gas extraction from fracking has been increasing and it may be technically and economically feasible to extract gas for plastic production while keeping oil-based fuel in the earth's crust. However, shale gas is also "fossil" carbon and incineration of shale-gas-based plastic waste could result in net emissions of CO_2. Long term production of fossil-carbon-based plastics is not consistent with framework of Paris Agreement unless permanent usage of plastics, infinite recycling, or eternal storage of plastic waste takes place. These processes are practically almost impossible and toxicologically risky. This points to very real possibility that the era of fossil-carbon-based virgin plastic will be phased out around 2050.

WHAT ARE MONOMERS, POLYMERS AND PLASTICS?

Plastics are essentially large units of smaller linked molecular building blocks called 'monomers'.

Monomers are made up of molecules which in turn are a group of atoms bonded together, representing the smallest fundamental unit of a chemical compound that can take part in a chemical reaction. When the monomers are joined together in chains and/or branching structures they are known as 'polymers'. Linear polymers (a single linear chain of monomers) and branched polymers (linear with side chains) are thermoplastic; they soften when heated. Cross-linked polymers, that is polymers with bonds formed between polymer chains, either between different chains or between different parts of the same chain, are thermosetting and harden when heated (Nkwachukwu *et al.* 2013).

Different types of polymers are made by linking together monomers with different chemical compositions using either linear or branched structures. These different types of polymers are what we commonly refer to as plastics, but each polymer also has a technical name based on its chemical and structural composition e.g. low density polyethylene, polyvinyl chloride and so on.

The chemical bonding process of linking monomers into polymers is called *polymerization.* Forming a single polymer may require thousands of monomers in chains. Common processes for polymerization include:

- **Condensation polymerization** – where the joining or polymerization is by water, carbon dioxide or ammonia. During condensation, two monomers join together and lose smaller molecules such as water or methanol. This process can be reversed during chemical recycling operations such as 'depolymerization' (see section 2).

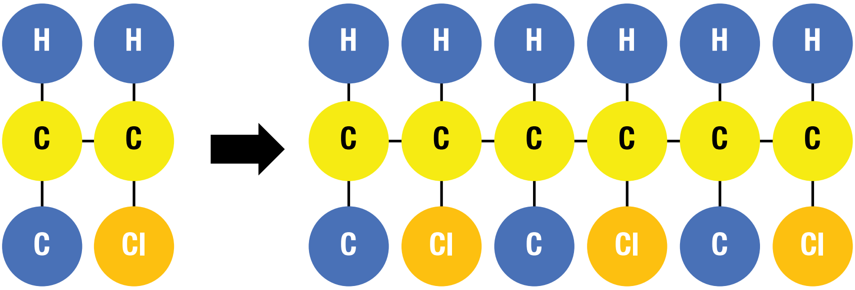


Figure 3. In this figure the monomer to the left is Vinyl Chloride. When linked together in chains the Vinyl Chloride molecules form Poly Vinyl Chloride or PVC.

- **Addition polymerization** (**polyaddition**) – where the join is formed by alkene catalysts such as ethene or propene.

Before the polymers can become a final plastic product that are treated with chemical additives that impart certain properties deemed desirable in the final product (UV-resistance, flexibility, color etc).

At this point the basic polymer material (pellets, nurdles or flakes) having been treated with additives can be cast, spun, extruded or otherwise shaped into the final plastic product.

These basic chemical and structural elements of plastics or polymers become important in the processes of mechanical and chemical recycling discussed below, as many of the challenges in recycling plastic relate to separating and reconstituting or mixing polymers.

Most currently produced plastics are made from petrochemical feedstock. Chemical engineering of petrochemicals allows for a vast array of different types of polymers, to be produced at industrial scale.

Global demand for plastic is dominated by a handful of polymers of the thermoplastic type: polypropylene (PP) (21%), low- and linear low-density polyethylene (LDPE and LLDPE) (18%), polyvinyl chloride (PVC) (17%), and high-density polyethylene (HDPE) (15%). Other plastic types with high demand are polystyrene (PS), and expandable PS (8%), polyethylene terephthalate (PET) (7%, excluding PET fibre) and the thermosetting plastic polyurethane (M.R.G. PlasticsEurope 2008, cited in Hahladakis *et al.*, 2018).

The sectors that generate plastic waste are dominated by packaging, textiles, consumer products, transport, construction, and electronics (Figure 4). Clearly the packaging sector is by far the greatest generator of plastic waste (much of it is single-use packaging), which is why it has been in the spotlight for visible plastic pollution in the environment.

TOXIC ADDITIVES

A significant challenge to the recycling of plastic is the widespread use of chemical additives in the formulations of polymers, many of which are inherently toxic. The recipe of additives in a plastic depends on the intended application of the polymer. Industry analysts estimate that the global plastic additives market for plasticizers, flame retardants, antioxidants, antimicrobial, UV stabilizers, and blowing agents will grow from USD 43.82 billion in 2018 to USD 61.25 billion by 2025 (Zion 2020). While some of the inert additives such as clays and talc are relatively benign, many additives are toxic to humans as well as environmental pollutants.

Additives can be divided into four main categories:

- Functional additives (stabilizers, antistatic agents, flame retardants, plasticizers, lubricants, slip agents, curing agents, foaming agents, biocides, etc.)
- Colorants (pigments, soluble azocolorants, etc.)
- Fillers (mica, talc, kaolin, clay, calcium carbonate, barium sulphate)
- Reinforcements (e.g. glass fibres, carbon fibres).

The most commonly used additives in different types of polymeric packaging materials are plasticizers, flame retardants, antioxidants, acid scavengers, light and heat stabilizers, lubricants, pigments, antistatic agents, slip compounds, and thermal stabilizers (Hahladakis *et al.,* 2018). Of the functional additives, plasticizers, stabilizers and flame retardants tend be of most concern to human health, but some colorants and fillers can also be problematic. Some of the most problematic functional additives are described below.

Flame retardant additives can be extremely toxic and have a high concentration by weight in the polymer, most especially among older waste electrical and electronic equipment (WEEE) plastics and automotive plastics. These additives commonly contain bromine compounds and are known as brominated flame retardants (BFRs). Plastics containing BFRs are produced in high volumes and have flame retardants added to reduce their flammability. In automobiles the plastics in dashboards, seating and

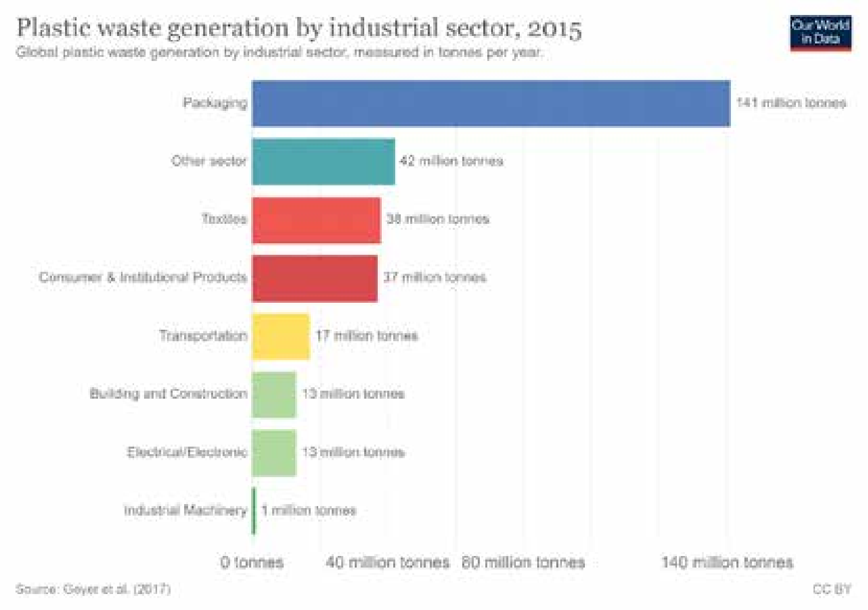


Figure 4. Plastic waste generation by industrial sector in 2015.

upholstery are often heavily treated with flame retardants with the intention of reducing the risk of fires. In electronics, the casings of TVs, computers and wire insulations are often treated with flame retardants due to the risk of fire from electrical short circuits etc. Some BFRs have been assessed as POPs and have been banned under the Stockholm Convention (e.g. Polybrominated dipheyl ethers (PBDE), Hexabromocyclododecane (HBCD or HBCDD)). These brominated POPs are known as POP-BFRs. Other brominated flame retardants may still be hazardous but have not been assessed as POPs.

Even after these additives have been banned, they continue to be present in plastic waste stockpiles for many years as the products they were used in may take years or decades to reach their end of life and enter the waste stream. Plastics containing POPs BFRs can generate dangerous exposure for recycling workers, including releases of brominated dioxins at the remelting and extrusion phase (He *et al.*, 2015, Huang *et al.*, 2013, Tang *et al.*, 2014, Labunska *et al.*, 2013). Unless carefully separated from polymers that are not contaminated by POP BFRs, these POPs can leak into the overall polymer recycling chain, ending up in products such as toys and kitchen utensils (IPEN, ARNIKA 2017a) that increase human exposure, especially among children (IPEN, ARNIKA 2018), as well as in food contact materials and household products (Puype *et al.*, 2015). Not all flame retardants are brominated. Short, medium, and long-chained chlorinated paraffins (SCCPs/MCCPs/LCCPs) have also been used extensively in plastics as both a plasticizer and flame retardant. Some flame retardants are so toxic and persistent that they have been identified as POPs and made subject to elimination through the Stockholm Convention. Specifically, Hexabromobiphenyl (HBB), commercial PentaBDE, commercial OctaBDE, commercial DecaBDE, Hexabromocyclododecane (HBCD), and short-chained chlorinated paraffins (SCCPs) have been added to the annexes of the convention as POPs.

Plasticizer additives also have a significant potential to impact on human health. Around 80% of all plasticizers are used in polyvinyl chloride (PVC) plastics and include short, medium, and long-chain chlorinated paraffins (SCCP/MCCP/LCCP), Diisoheptyl phthalate (DIHP), 1,2-Benzenedicarboxylic acid, di-C7-11 -branched and linear alkyl esters (DHNUP), Benzyl butyl phthalate (BBP), Bis(2-ethylhexyl) phthalate (DEHP), Bis(2-methoxyethyl) phthalate (DMEP), Dibutyl phthalate (DBP), dipentyl phthalate (DPP), di-(2-ethylhexyl) adipate (DEHA), di-octyladipate (DOA), diethyl phthalates (DEP), diisobutyl phthalate (DiBP), Tris(2 chloroethyl) phosphate (TCEP), dicyclohexyl phthalate (DCHP), butyl benzyl phthalate (BBP), diheptyl adipate (DHA), heptyl adipate (HAD), and heptyl octyl adipate (HOA), while the remaining 20% are used in cellulose plastic (Hahladakis et al., 2018).

The plasticizer group of additives are dominated by phthalates, which can have significant health impacts when they leach or migrate out of the polymer structure. They can also have impacts when the plastic reaches its end of life, degrades in the environment, leaches into landfill, or is burned. Phthalates are a known endocrine disrupting chemical (EDC) capable of disrupting the hormonal system of humans. This means they can have far-reaching and devastating impacts on the fetus through childhood development and into adulthood.[3] EDCs can also have serious impacts on the ability of wildlife and aquatic organisms to develop and on their ability to reproduce. Plasticizers are commonly used in flexible food packaging and food contact materials as additives to the polymer packaging. Phthalates are used in large volumes in PVC.

EDCs and their impacts on human health are a growing area of scientific research. Their impacts can be unpredictable and difficult to manage, according to existing regulatory frameworks such as linear dose-response relationships (i.e. that the dose makes the poison) as assessed by risk assessment frameworks. EDCs can impact human health at very high levels

---

[3] *Introduction to Endocrine Disrupting Chemicals (EDCs)*, 2014. https://ipen.org/documents/introduction-endocrine-disrupting-chemicals-edcs

but also at very low levels, especially during the early development of the fetus and other sensitive developmental windows. The ability to impact health in a non-linear dose relationship defies established threshold-level assessments used to predict the potential harm of a chemical. As noted in a 2014 Endocrine Society/IPEN publication, a positive correlation between chemical and plastic production and EDC effects in humans is evident:

> *"There is good reason to suspect that increasing chemical production and use is related to the growing incidence of endocrine-associated pediatric disorders over the past 20 years, including male reproductive problems (cryptorchidism, hypospadias, testicular cancer), early female puberty, leukemia, brain cancer, and neurobehavioral disorders. At the same time, the global production of plastics grew from 50 million tons in the mid-1970s to nearly 300 million today, and sales for the global chemical industry have sharply increased from USD $171 billion in 1970 to over USD $4 trillion in 2013. Chemicals such as polychlorinated biphenyls (PCBs), BPA, and phthalates, are now detectable in serum, fat, and umbilical cord blood in humans around the globe."*

There are many routes by which EDCs additives can leave plastics and cause exposure to humans. For instance, Bisphenol-A (BPA), is a very commonly used plasticizer and another known EDC that has been reported to migrate into food from plastic baby bottles (Kubwabo *et al.*, 2009, Nam *et al.*, 2010), heat-affected food can coatings (Goodson *et al.*, 2004), and other types of food packaging (Fasano *et al.*, 2012). Many food packaging containers are now produced 'BPA-free', but BPA is a high-volume chemical and common in plastics so exposure can continue from a variety of sources.

Toxic additives from plastic enter the environment in a range of ways through emissions, releases, degradation, leaching, and migration (Figure 5) at many stages during the production, use, and end of life of the plastic they have been added to. The propensity of additives to leave the polymer is increased by the fact they are not chemically (covalently) 'bound' in the polymeric chain but rather are dispersed between monomers (Figure 6). This allows a greater propensity to migrate out of the polymer into the environment during all phases of the lifecycle of plastics.

Different plastics can leach different additives at varying rates. If a polymer has a higher permeability, then it can leach additives at a faster rate. Different physical structures of plastics such as hard crystalline or rubbery flexible plastic can affect the leaching process. More flexible or rubbery polymers have larger gaps in the polymer structure and can leach more

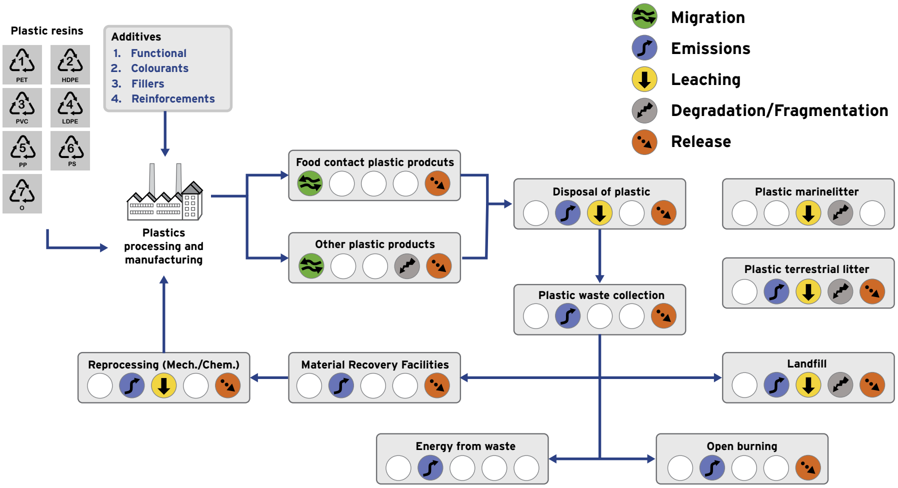


Figure 5. The pathways by which additives to common plastics reach the environment. Source: Hahladakis *et al.* 2018

readily than a hard, crystalline structure. In addition, a low molecular weight additive can leach more quickly from the polymer matrix. The amount of additive that can leach from plastic depends on many factors, including weathering and temperature, but is ultimately limited by its proportion of the total plastic mass, which can be surprisingly high. PVC can contain more than 40% by weight of plasticizers such as phthalates (BLASTIC 2019).

Mechanical recycling cannot separate additives from the recyclate it creates. Chemical recycling has much greater ability to do so because it reduces plastic waste to molecular, monomer or polymer levels, separating them from the additives.

Of all technologies discussed below for management of plastic waste, supercritical and subcritical water oxidation (SCWO and iSCWO) are the only depolymerization technologies that have a recyclate output that does not contain the residues of chemical additives, a waste rich in toxic additive residue or emissions that convert additives to unintentionally produced POPs (UPOPs), (as is the case with incineration and pyrolysis technologies). The additives, including POPs, are destroyed in the depolymerization process. Depolymerization of plastics using SCWO and iSCWO have discharges of carbon dioxide, water, and depending on the waste feed, salts and/or metallic oxides. Steam is vented to the atmosphere. There are no particulates released or pollution-abatement filters required.

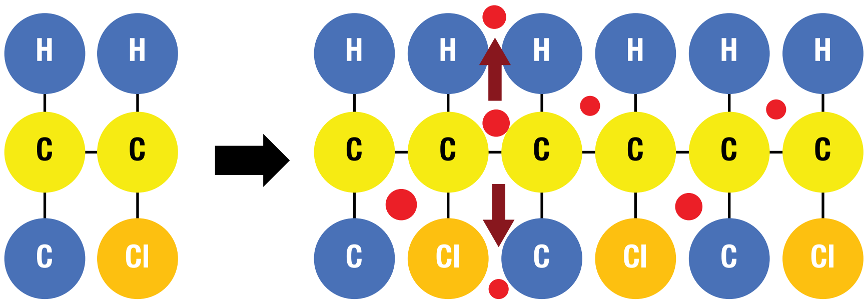


Figure 6. Additives (red dots) are not chemically bound to the polymer chain and can leach out of the plastic structure.

Clean water is produced requiring no pre-treatment before sewer disposal (elevated salinity and metal oxides limit the use of the effluent water).

ADDITIVES OF GLOBAL CONCERN: PHENOLIC BENZOTRIAZOLES UV -326, UV-327 AND UV-328

Stabilizer additives have not received as much attention in the literature as some other additives but have recently been the subject of increased concern. Ultraviolet (UV) light stabilizers function by preventing degradation of plastic through competitive absorption of UV light. In the past the main concern has been associated with heavy metal-based UV stabilizers in PVC such as lead and cadmium with readily leach into the environment and rightly so.

However, another group of UV stabilizers, based on *phenolic benzotriazole (BT)* are of growing concern to chemical regulators. This is mainly because they share a phenolic structure which is the necessary structure for molecules to bind with the human estrogen receptors and therefore have the potential to exert endocrine disrupting activity. The BT family, including UV-326, UV-327 and UV -328 also demonstrate persistent, bioaccumulative and toxic properties.

The *benzotriazole* stabilizer UV-328 (2-(2H-benzotriazol-2-yl)-4,6-ditert-pentylphenol) has been found to exhibit persistent, bioaccumulative and toxic (PBT) properties to such as extent that it may be a POP substance meeting the Stockholm Convention criteria. This has resulted in a proposal by Switzerland (UNEP 2020) to list UV-328 on Annex A of the Stockholm Convention which, if successful, would result in its classification as a POP and subject it to global elimination.

UV-328 has also been identified by the Member State Committee of the European Chemicals Agency (ECHA)[4] as a Substance of Very High Concern (SVHC) and added to Annex XIV 'Authorisation list' of the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation, with a sunset date of November 27th, 2023. All uses after this date requires a formal authorization by ECHA.

Other similar stabilizers from the *phenolic benzotriazole* group have also been added to the Authorisation List including UV-320, UV-327 and UV-350. These stabilizers all meet the REACH criteria of PBT and very Persistent and very Bioaccumulative (vPvB) substances and were confirmed on the Authorisation List in February 2020.[5] UV-328 is highly hydrophobic, adsorbs and/or absorbs strongly to organic material, and has a low tendency to volatilise. When released to water, it will likely partition to particles and organic matter, suspended or deposited. Experimental and estimated data indicate that UV-328 does not degrade rapidly in water, soil, or sediment. It has been measured in sediment (along with UV-327) near an industrial release site in Narragansett Bay, USA decades after release stopped (Cantwell *et al.,* 2015). It has been detected in multiple studies in aquatic life, foodstuffs and human adipose tissue (UNEP 2020)

UV-328 and related benzotriazoles (i.e., UV-326 and UV-327) can be transported long distances in plastic resin pellets and plastic fragments especially in aquatic environments, resulting their detection in plastics on remote islands (IPW 2020). They have also been detected in plastic fragments ingested by seabirds (Tanaka *et al.*, 2019). Furthermore, they were also found to accumulate in preen gland oil of wild seabirds from remote islands from plastic ingestion (Tanaka *et al.*, 2020), indicating their bioaccumulative nature. UV-328 and associated BT are considered to be toxic for mammals, endangering human health and the environment, as it may cause damage to liver and kidneys through prolonged or repeated oral exposure (UNEP 2020). The Swiss proposal to the Stockholm Convention also notes that that pharmacokinetic modelling indicates that BT based UV stabilizers such as UV-326, UV-327 and UV-328 are absorbed into the gastrointestinal tract, metabolised in the liver, and excreted via kidneys and that this leads to liver and kidney toxicity (UNEP 2020).

There are high levels of concern about UV-328, UV-326 and UV-327 both because of their PBT properties but also because of their widespread use in common plastics allowing for high levels of human and environmental exposure. UV-328 is a high production volume (ten of thousands of tonnes globally) chemical used as a UV stabilizer in plastics. The range

---

[4] https://echa.europa.eu/substance-information/-/substanceinfo/100.043.062

[5] ECHA. *Estimating the number and types of applications for 11 substances added to the Authorisation List in February 2020.* (2020) doi:10.2823/11134.

of polymer types and plastic types incorporating UV-328 is broad and includes: polyolefin and plastic shrink films (e.g. food contact shrink wrap), plastic outdoor furniture, ABS resin, epoxy resin, fibre resin, PVC (e.g. construction materials and food packaging), unsaturated polyesters, polyacrylates (e.g. paints, textiles, leather finishing) and polycarbonates. It is particularly recommended as UV absorber for polyolefins (e.g. bottle caps, plastic bottles, plastic wrap), polyurethanes, PVC, polyacrylate, epoxy and elastomers.[6] UV-328 as a high-volume plastic additive with production and/or importation in the European Economic Area in the range of 100-1000 t/a and 450–4,500 t/a in the US.[7]

The ubiquitous nature of BT UV stabilizers in plastic was supported by a recent study[8] from International Pellet Watch who sampled marine litter plastic fragments collected in remote coastal locations and analysed the fragments for UV stabilizer additives. The results demonstrated that while UV-328 was detected in many samples, even higher concentrations of UV-326 and UV-327 were present in most of the fragments (see Figures 8 and 9).

Regulatory agencies for chemical management are increasingly concerned about the persistent, bioaccumulative and toxic properties of benzotriazole UV stabilizers. While some of the benzotriazole UV stabilizers exhibit PBT characteristics to a lesser or higher degree (with UV-328 currently assessed as the most hazardous) the precautionary principle should apply and lead to the rapid phase out of this family of UV stabilizers.

If UV-328 is assessed as a POP and added to the annexes of the Stockholm Convention the plastic recycling industry will need to develop detection systems to ensure that this chemical does not contaminate the recycling stream and recirculate into new products made from recycled plastic. In addition, the management of plastic waste contaminated by POPs requires that it be destroyed or irreversibly transformed so that it does not exhibit POP characteristics. Given the high-volume production and use as additives in a wide variety of polymers it is important that the process of evaluation and phase out of the BT family of stabilizers be accelerated.

PLASTIC RECYCLING

As the pressure to deal with plastic waste grows daily, new technologies and concepts for plastic waste management arise apace. Many of these

---

[6] Ibid.

[7] ECHA. High-volume plastic additives mapped. (2019).

[8] International Pellet Watch (2020) Global survey of benzotriazole-type UV stabilizers in microplastics (pellets and fragments) unpublished data.

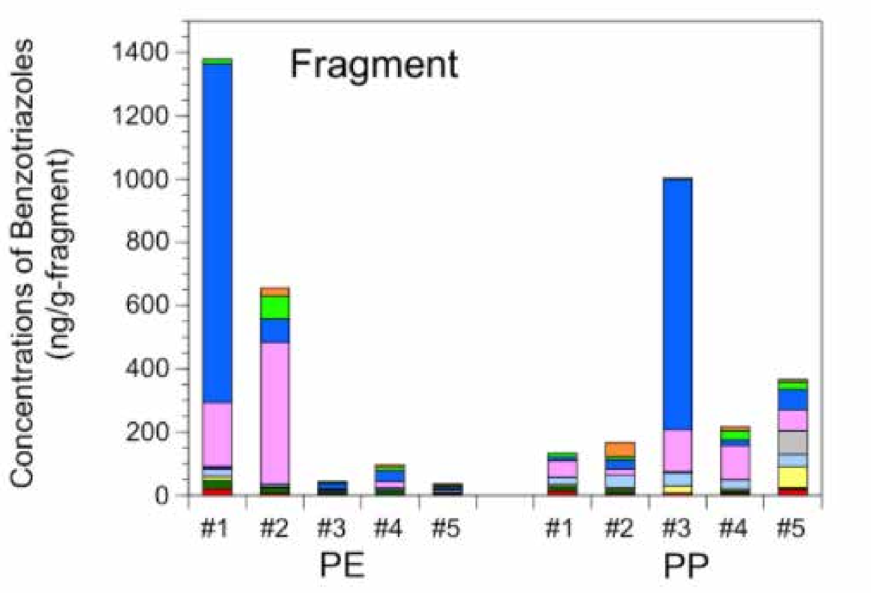


Figure 7. Benzotriazole (BT) UV stabilizers in 5 polyethylene and polypropylene fragments from remote coastal locations. Source: International Pellet Watch 2020

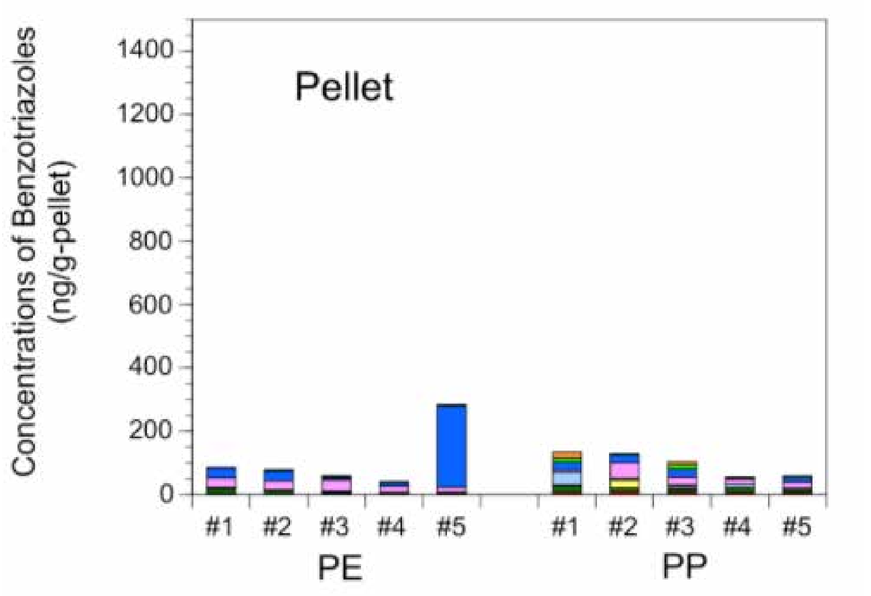


Figure 8. BT UV stabilizers in pellets samples from remote coastal locations. Source: IPW 2020

so-called solutions lead to further contamination issues or simply do not work. Others seem completely at odds with a carbon-constrained future. Yet others seem to ignore the fact that many plastics contain toxic chemical additives and redirect these materials into inappropriate scenarios increasing human exposure. It is unlikely that the vast variability in plastic waste can be addressed by any single, silver bullet, technical solution. The reality is that multiple technical and social approaches will be needed, and they will all need to be assessed for their ability to operate with environmentally sound outcomes across a range of criteria. These would include toxic outputs and redistribution, carbon footprint, ability to contribute to a circular economy, and environmental justice (not dumping plastic waste on low-income countries and communities), among others.

Existing and emerging approaches to plastic waste management that some claim are solutions to the plastic waste problem include:

- Mechanical recycling
- Chemical recycling
- Downcycling (use in road surfacing, etc.)
- Plastic to fuel
- Plastic to energy (waste incineration)
- Reuse
- Landfill

This report focuses on mechanical and chemical recycling and associated plastic to fuel approaches. However, no meaningful comparison of these approaches can be made without acknowledging that many plastics are not benign in nature. Indeed, the Canadian government plans to list plastics as toxic under Schedule 1 of the Canadian Environmental Protection Act (CEPA) to allow them to ban certain uses of polymers.[9]

As noted above, in order to impart specific characteristics (color, pliability, durability, fire resistance, and so on) many polymers contain chemical additives that are toxic and hazardous. Large volumes of plastics are also infused with the extremely toxic group of chemicals known as persistent organic pollutants (POPs). These plastics should not be recycled at all and must be destroyed unless they can be decontaminated.

---

[9] https://www.theglobeandmail.com/canada/article-ottawa-set-to-declare-plastics-as-toxic-substance/ https://www.canada.ca/en/health-canada/services/chemical-substances/other-chemical-substances-interest/plastic-pollution.html

This means that a management approach that might suit a PET plastic water bottle may be completely inappropriate for a plastic dashboard from a car that contains a high percentage of POPs, like brominated flame retardants. Research demonstrates that many of these POPs-contaminated plastics ‘leak’ POPs into their environment while still in use, contaminating household dust, car interiors, and office spaces (Whitehead *et al.*, 2013). Concentrating these plastics as waste into management facilities, processing technologies, and recycled products can lead to unintended and extremely hazardous workplaces, emissions, exposures, and products, as POPs can leach out and adsorb to dust in these settings (Bi *et al.* 2010). Options for the management of end-of-life POPs-contaminated plastics are described in more detail in section 5.

For decades, plastic recycling has almost entirely been dominated by the mechanical recycling sector which sorts, cleans, shreds, extrudes, and pelletizes polymers back into feedstock for the plastic manufacturing sector or supplies plastic recyclate for various forms of downcycling. Chemical recycling (for polymers or fuels) has been limited mostly to trials with a few pilot plants established. Supercritical water plants for specialized depolymerization have been operating for around 20 years.

Despite these efforts, plastic recycling has had a minimal impact on reducing environmental plastic pollution, and even less on substituting polymers and reducing overall virgin plastic production. When oil prices are low, it is extremely difficult for recycled plastic to compete with virgin materials. Estimates[10] suggest global plastic recycling rates in 2015 were 19.5% compared with incineration rates of 25.5%, and 55% landfill/open dumping rates (Figure 13). Extrapolation of current trends to 2050 would see recycling rise to 44%, but incineration rise to 50% of all plastic produced in that year. Based on the forecast projection of production of plastic at 1 800 million tons for the year 2050 (Ryan 2015) and extrapolation of disposal methods on current trends (Geyer 2017) approximately *900 million tons of plastic* will be incinerated in the same year. These figures infer that incineration will mostly replace landfilling and open burning, which will be reduced to 6% of all plastic produced. However, that 6% still represents a staggering 108 million tons of plastic waste destined to enter the environment or being openly burned in the year 2050 alone.

IS IT REALLY RECYCLING OR JUST EXPORT?

While much of the following discussion is around technical issues detailing which technologies can recycle which polymers using different techniques, it must be recognized that there is an international, environmental

---

[10] https://ourworldindata.org/plastic-pollution

justice component to be considered. Most low-income countries do not have the financial or technical capacity to establish sophisticated recycling infrastructure. Many cannot afford to even develop adequate sanitary landfills. Images of rivers filled will plastic waste flushing out to sea are common. On land, enormous amounts of plastic waste are being openly dumped or burned to reduce the waste volume. Burning plastic waste generates airborne toxic compounds leading to exposure of large populations. The toxic chemicals, including POPs, build up in the soil and contaminate the food chain – at times to extraordinary levels. IPEN studies of open plastic waste dumping and burning in Ghana[11] and Indonesia[12,13,14] demonstrate severe food chain contamination by POPs such as dioxins at levels only seen at sites in Vietnam heavily contaminated with Agent Orange.

Wealthy countries dramatically exacerbate this problem by exporting plastic waste to low-income countries under the guise of recycling, knowing full well that the countries they export the waste to have very limited capacity to recycle the plastic. In many cases, the exported waste contains high volumes of plastic that cannot be technically or economically recycled *anywhere*. A large proportion of the plastic waste that caused the food chain contamination revealed in IPEN's reports was imported from wealthy countries. For decades, citizens in many developed countries have dutifully separated their wastes for curbside collection assuming that their plastic was being recycled in their own country. The reality is that much of it is exported, landfilled, or burned in incinerators.

When China implemented its National Sword Policy in January 2018, blocking imports of mixed and contaminated plastic waste, wealthy countries shifted their exports to countries in Southeast Asia, including Thailand, Vietnam, Malaysia, Indonesia, and the Philippines. Within two years many of these countries began to reject such shipments due to high levels of contamination and limited means to manage even the recyclable content. In turn, this has shifted the focus back onto wealthy countries to deal with their own plastic waste and onto the producers of the plastic who are now scrambling to placate public opinion with 'solutions' to the problem they have created. The main focus of plastic producers is to propose a large-scale expansion and acceleration of technologies for *chemical recycling* of plastic waste. The analysis in this report demonstrates that chemical recycling in the context of the current crisis is largely a public

---

[11] https://www.researchgate.net/publication/332594125_Persistent_Organic_Pollutants_POPs_in_Eggs_Report_from_Africa/download

[12] https://ipen.org/news/plastic-waste-poisons-indonesia%E2%80%99s-food-chain

[13] https://www.nytimes.com/2019/11/14/world/asia/indonesia-tofu-dioxin-plastic.html

[14] https://www.theguardian.com/global-development/2019/nov/15/indonesias-food-chain-turns-toxic-as-plastic-waste-exports-flood-in

relations distraction that will have little impact on the problem of plastic waste.

PLASTIC RECYCLING IN LOW-INCOME COUNTRIES

Environmentally sound management of plastic waste requires carefully designed municipal and industrial waste collection, separation, and cleaning or pre-treatment systems before the main process of recycling can be undertaken. In wealthy countries, these systems range from poor to adequate and mirror the relatively poor recycling rates for most polymer types. However, in low-income countries very little of this 'front end' infrastructure exists, or if it does, it looks very different to that of wealthy countries. In low-income countries, much of the collection and separation is conducted by waste pickers.

Waste pickers are often very low paid, vulnerable populations who hand-pick recyclable material from the streets, from openly dumped waste, and from landfills as new waste loads arrive. They usually have no effective protective equipment and are exposed to contaminated materials, disease, and risk of injury. Despite their vulnerability and informal approach to gathering recyclables from waste, they are surprisingly effective and in some countries are at the forefront of national recycling efforts. In general terms, their motivation is not to protect the environment; they have far more pressing concerns, such as paying for food and shelter to survive. They must innovate to survive, and through their informal networks, have developed some simple techniques for processing and separation of complex polymers.

In India, the informal plastic waste recycling sector has developed a range of identification and separation tests for different polymers, including BFR-contaminated plastics from WEEE. Some of the techniques are very dangerous when conducted repeatedly, such as the Beilstein test for identifying brominated plastics. This test involves heating copper wire in a cigarette lighter flame until glowing and bringing it into contact with a plastic flake, after which it is held in the flame again. A green flame indicates the presence of halogens and is characterized as a positive Beilstein test (Haarman and Gasser 2016). Such a process has high potential to release toxic gases and brominated dioxins. Other separation tests based on flotation and differing density of polymers also allow for efficient separation without such acute risks (though contamination in processing areas is likely).

In Indonesia, some villages have turned to 'plastic farming' to supplement agricultural incomes. Bales of paper waste exported from the UK, Australia, and Canada contain a high degree of plastic waste contamination – a

Figure 9. Waste pickers, New Delhi. Source: Altaf Qadri

small fraction of which has value as a recyclable polymer. The paper mills that import the bales for recycling dump truckloads of the plastic contaminants at local villages for a small fee or for free. Villagers pick through the waste and obtain a small amount of income for the recyclable content that supplements their agricultural income. However, the vast majority of the material is dumped and burned around the village. In some cases, the plastic waste is even burned for fuel in factories emitting black toxic smoke and contaminating the local environment.

Sampling of free-range chicken eggs by IPEN and partner organizations Ecoton and Nexus3 Foundation, in the villages of Tropodo and Bangun, Indonesia[15], found that burning plastic waste in tofu kilns and in the open, respectively, caused serious food chain contamination (Figures 12 and 13). The levels of highly toxic dioxin found in the eggs were the among the highest ever recorded in Asia.

While there are some case studies of innovative techniques and efficient recycling, the reality for many waste pickers in developing countries is a life of poorly paid, risky, and dirty work. The impact of the waste they must sort through is contaminating their environment and their food chain, leading to exposure to toxic chemicals for generations to come. The current corporate push for capital-intensive, energy-intensive, high-tech chemical recycling will have little impact on the income, work conditions,

---

[15] https://ipen.org/news/plastic-waste-poisons-indonesia%E2%80%99s-food-chain

Figure 10. Grinding, float separation and sorting by informal recyclers, India.
Source: Haarman and Gasser 2016

and outcomes for waste pickers and their communities, who are collectors and not processors.

Implementation of environmentally sound waste management systems with adequate recycling infrastructure in low-income countries is certainly needed. Decent wages and protective conditions for recycling workers are also a necessity. Export of low-grade plastic waste from wealthy to low-income countries should be more tightly regulated by the implementation of the recently agreed Basel Convention plastics amendment. When the amendment enters into force in January 2021, this type of low value, mixed plastic waste will no longer be exportable from wealthy countries to low income countries with the prior informed consent of the importing party. For plastic waste that exhibits the characteristics of hazardous waste, export will be banned by the Basel Ban Amendment which came into force on 19th December 2019.[16] However, even with all of this in place, it will not prevent large-scale plastic waste pollution of the environment. Only a cap on the unprecedented expansion of plastic production will begin to address the core issue of plastic waste.

---

[16] https://ipen.org/documents/basel-ban-amendment-guide

A couple in Bangun village collect plastic scraps to sell. The small amount of recyclable plastics are bought by recyclers, low-grade scrap is sold to local factories for fuel. Photo: Nexus3

WHAT PLASTIC ACTUALLY GETS RECYCLED AND WHAT DOES NOT?

The answer depends, to some degree, on which country you live in. As noted in the previous section, low-income countries lack the developed infrastructure to recycle even the most easily recycled polymers. Much of the plastic waste ends up in the environment, burned or choking waterways, and contaminating the ocean. In wealthy countries with adequate waste management infrastructure, it is possible for more plastic waste to be recycled, however market conditions currently ensure that large amounts of plastic waste are incinerated, landfilled, or exported. The issue is usually not what can technically be recycled but what can *economically* be recycled.

Most plastics that are labelled as recyclable with a triangular circulating arrow with a resin code number in the center (see Figure 14) are not

Figure 11. Smoke from plastic-burning tofu factories in Tropodo, Indonesia.
Source: Ecoton

Figure 12. Informal recycling of plastic waste. Bangun, Indonesia. Source: Ecoton

economically recyclable and become waste. The most recycled polymers are PET (RC 1) and HDPE (RC 2). Polymers such as PVC (RC 3) and polypropylene (RC 5) are generally not accepted for recycling. Polystyrene (RC 6) also has low recycling rates. These resin codes and the recycling symbol that surrounds them were developed by The Society of the Plastics Industry (SPI) at a time when regulatory bans on some types of plastic were gaining traction. They were designed to focus consumers on the issue of recycling and not on the issue of environmental impacts of plastics. However, within the plastic industry, recycling was not considered viable, and research suggests the SPI did not believe that recycling could be economically viable.[17]

The plastics industry has long used the resin codes in the recycling symbol to convince consumers that plastic is recyclable. The reality is that this is a misleading marketing ploy to avoid plastic bans. While many polymers can technically be recycled under laboratory conditions, the reality is that the economics of commercial scale recycling don't add up. A key constraint is the ability of recyclate to compete with virgin polymer in the marketplace. When the price of oil, the petrochemical building block of plastic, is low recyclate cannot compete. Even if it could, the market for recycled plastics is weak due to concerns about the functionality of recycled polymer compared to virgin polymer. Despite these barriers some plastic is recycled or downcycled into new uses.

The preferred plastic waste for recyclers is post-industrial (PI) plastic waste such as runners from injection moulding, waste from production changeovers, cuttings and trimmings as they are relatively contamination free and often occurs as polymer 'mono-streams', which are uncontaminated by other polymers and have not been subject to degradation through use and wear (Ignatyev *et al.* 2014).

Clean, post-consumer plastic waste is the next preferred input to recycling, but in reality, most post-consumer plastic waste is mixed polymer with varying degrees of contamination, both by organic waste and other polymers. By far, the largest fraction of plastic waste is from packaging (which also has the largest share of production), and it is dominated by the five biggest global production volume plastics; (high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP) and polyethylene terephthalate (PET), and poly vinyl chloride (PVC).

In theory, most plastics are recyclable. But as explained in the sections below, there are many technical and economic barriers to recycling plastics, including energy use, contamination, toxic additives, and laminated

---

[17] https://www.pbs.org/wgbh/frontline/film/plastic-wars/

constructions. However, potentially recyclable polymers are identified in Figure 14 by recycling symbols developed by the Society of the Plastics Industry (SPI) in 1988. In reality, only RC codes 1 and 2 are commonly recycled. While other RC polymers may be technically recyclable in a laboratory a range of reasons, including economics, mitigates their ability to be recycled in a viable way.

Generally, the lower the resin code (RC) number, the more likely it is to be recycled. In reality this translates to PET and HDPE. The higher the RC code the less likely the plastic is to be recycled due to economic or environmental reasons. Polystyrene (RC 6) takes both a rigid form (yoghurt containers, plastic cutlery, and CD cases) and a foam. Expanded polystyrene (EPS) foam is used for coffee cups, fridge insulation and packaging of electronic goods. This is different from Styrofoam™ which is a closed-cell extruded polystyrene (XPS) used in building insulation. A significant fraction of existing XPS contains POPs BFRs to limit fire potential in buildings. While the Stockholm Convention exemption permitting the use of the BFR Hexabromocyclododecane (HBCD) in building insulation expired in 2019 (meaning it can no longer be added to XPS), the legacy of existing installed insulation will have to be managed for decades as buildings constructed in recent decades reach their end of life and are demolished in the future. RC 7 includes styrene acrylonitrile (SAN), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), and nylon which are rarely recycled using mechanical processes.

A low RC does not necessarily make the polymer easy to recycle. As an example, plastic films, plastic wrapping, and thin plastic bags using low density polyethylene (RC4) often clog recycling process machinery when mixed with heavier plastics, resulting in low recycling rates for this polymer.

In terms of consumers goods, the following polymers are used for specific products, but only RC 1 and RC 2 are commonly recycled:

- **Resin code 1:** PET typically includes drink bottles, medical containers and cups. Recycled PET can become fiberfill for winter coats, sleeping bags, and life jackets.
- **Resin code 2:** HDPE is one of the most commonly recycled post-consumer plastics. It is the stiff plastic used to make milk containers, detergent and motor oil bottles, toys, and some plastic bags.
- **Resin code 3:** PVC includes rigid plastics like pipes and tubes but also food wraps, vegetable-oil bottles and blister packages, shower curtains, medical tubing, and car dashboards.

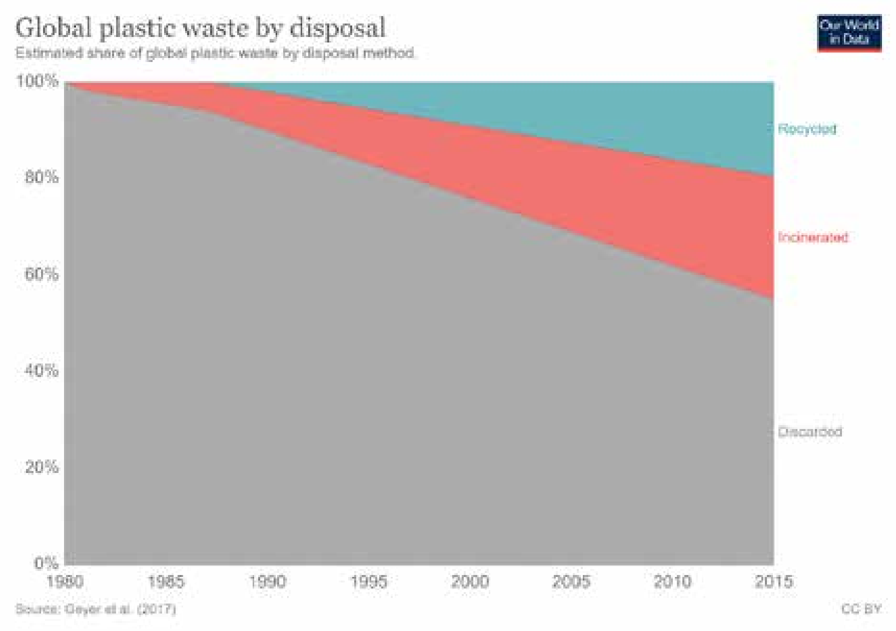


Figure 13. Global plastic waste recycled, incinerated or dumped 1980 – 2015. Source: Geyer *et al.* 2017, cited in Our world in Data.

- **Resin code 4:** LDPE is light weight, thin and flexible, and is commonly used for beer six-pack fasteners and plastic bags, including zip lock bags.
- **Resin code 5:** PP is used in food containers, some plastic car parts, and caps for bottles.
- **Resin code 6:** PS is used to hold food, drinks cups and some plastic utensils.
- **Resin code 7:** A general-purpose category for acrylic, nylon and other plastics.

Plastics that cannot legally be recycled or which are very difficult to recycle include:

** CreaSolv® can potentially manage these waste streams but currently has limited commercialization.*

- POPs-contaminated plastic[18] (see section 5).
- Laminated plastics* (multiple-layered packaging including foil, polymer, and paper) such as snack packets and take-out coffee cups.
- Plastic films (agricultural silage wrap, cling film, etc.).
- Most items in RC 3, 4, 5 and 7.
- XPS with BFR additives*.

The following section challenges the assumption that chemical recycling is really the silver bullet for plastic pollution as suggested by the Fast-Moving Consumer Goods companies (FMCGC) and petrochemical corporations who are heavily promoting chemical recycling as a solution for plastic waste.

PVC - THE POISONOUS POLYMER

Polyvinyl chloride or PVC stands out as one of the most difficult plastic wastes to manage and causes serious problems for the recycling of other plastics. It comes in two forms, rigid and flexible. The more flexible form of PVC has plasticizers added such as phthalates. The flexible form is used as flooring, imitation leather, and cable insulation, but also as trays for sweets, fruit packaging, bubble foils, and other food packaging. The rigid form is mainly used in construction for water pipes, window frames, doors, and so on.

PVC has a high toxicity potential due to the relatively high content of chlorine (vinyl chloride is a class A carcinogen, toxic to the liver) in its formulation and a range of additives, including high concentrations of phthalates, and to a lesser extent lead and cadmium, which are added as stabilizers. PVC generates problems when burned in incinerators, as the chlorine content of PVC, which varies between products but can be as high as 57%, acts as a catalyst for the generation of dioxins and other UPOPs (Katami *et al.,* 2002). Many municipal waste incinerators have a clause in the operating licence that excludes PVC as a permitted waste to try and avoid additional dioxin generation. When buried in landfills, lead, cadmium and phthalates can leach from PVC to contaminate groundwater. When burned in the open, as is the case in many developing countries, PVC (and other halogenated plastics) produce hazardous acid gases, di-

---

[18] Article 6 1. (d) (iii) of the Stockholm Convention prohibits the recycling of waste materials (including plastic) containing POPs above the low POP content level. However in recent years, exemptions were permitted for some brominated diphenyl ethers leading to contamination of the plastic recycling chain.

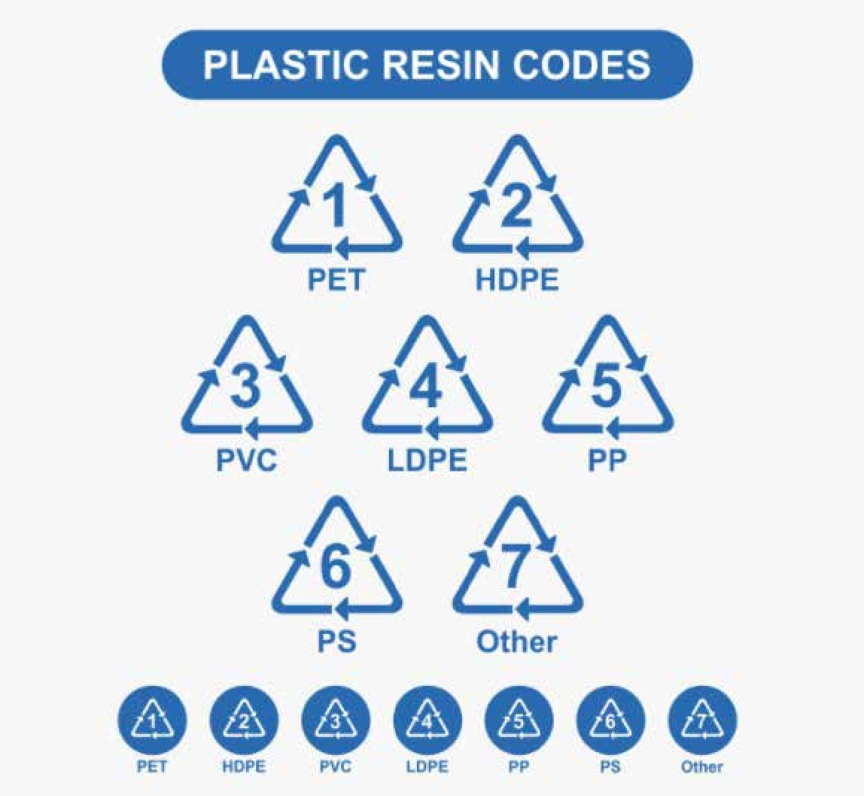


Figure 14. Potentially recyclable polymers. SPI 1988

oxins, and other UPOPs, especially if combined with plastics treated with brominated flame retardants (Weber and Kuch 2003).

In landfills, phthalates migrate from PVC at high concentrations into the leachate and eventually into groundwater (Wowkonowicz and Kijeńska 2017). Lead and cadmium stabilizers also present a leaching problem (Mersiowski and Ejlertsson 1999; American Chemical Society 2008).

The high concentration of phthalates in flexible PVC has been a significant concern due to the endocrine disruption potential of phthalates. In PVC, medical equipment is a particular concern due to the exposure scenario for patients and phthalate concentrations of up to 40% by weight for intravenous medical bags and up to 80% by weight in medical tubing (Halden 2010).

PVC has lead added as a stabilizer, but this has been found to readily leach out during use, contaminating drinking water in PVC pipes. In the

EU, lead was phased out of PVC by 2015, but overseas imports may still contain lead.

PVC and its building blocks cause significant pollution and hazardous exposure during production, during use, and at its end of life. The building block for PVC's manufacture is the production of vinyl chloride monomer (VCM). Production of VCM in China, one of the world's largest producers of PVC, differs from most VCM production elsewhere in the world. Due to an abundance of coal and limited reserves of gas, China uses acetylene derived from coal instead of ethylene from gas to produce VCM. This coal-based manufacture of VCM combines acetylene with hydrogen chloride, and they flow through a mercuric chloride catalyst to produce VCM.[19] This production process results in large quantities of mercury emissions to air, as well as mercury waste and releases. Since the early 1970s, VCM has been recognized as an occupational carcinogen (Creech and Johnson 1974).

When PVC enters the recycling system, it is imperative that it is separated from other polymers to prevent contamination of the plastic recycling output. In practice, this separation can be very difficult and expensive to carry out as plastics may arrive at the recycling facility in pieces, making identification even more challenging. When attempting to recycle PVC back into PVC by mechanical means, the problem is that PVC has many different formulations beyond simply rigid and flexible characteristics requiring varying levels of chlorine and additives. Mixing these together results in a poor quality of recyclate which is unlikely to meet the specific input needs of PVC manufacturers, and cause loss of structural integrity in the final product made from the recyclate.

When PVC is mixed with other types of polymers in a mechanical recycling process, there are similar issues and the PVC effectively 'contaminates' other polymers, degrading their structural properties and inhibiting production processes such as extrusion. When processing mixed polymers, the recycler is forced to heat the mixed polymers to the highest polymer melting point of the mixture. This can lead to overheating and degradation of lower melting point polymers in the mix. This is the case when PET and PVC are heated together to the higher melting point of PET, causing accelerated dehydrochlorination of the PVC.

Chemical recycling of PVC also suffers from difficulties associated with chlorine and phthalate additives. The presence of even small amounts of PVC in the input plastic stream of a pyrolysis unit leads to contamination of the output polymers by hydrochloric acid (HCl), which must be re-

---

[19] https://ipen.org/sites/default/files/documents/ipen_mercury_booklet-en.pdf

moved. Hydrochloric acid is highly corrosive and imposes severe metallurgical constraints on the process equipment of the pyrolysis unit. If the pyrolysis output is an oil or wax, even very small amounts of halogens prevent its use as fuel or feedstock (Ragaert *et al.*, 2017).

Phthalate additives also challenge solvent processing. An example of how additives can relegate recycling unviable is the closure of the VinyLoop plant in Italy which operated since 2002 but shut down in 2018 because it could not economically separate the substantial amounts of phthalate plasticizers used in soft PVC to meet EU regulatory requirements (European Commission 2018).

2. CHEMICAL RECYCLING OF PLASTIC

The term ‘recycling’ has been subject to considerable definition creep in recent years. It may once have been understood as simply using the material in one discarded article to contribute, in part or whole, to the remanufacturing of that same type of article or a different one. Now the definition has become more elastic. Some propose that it includes turning discarded plastic and other waste into fossil fuels to burn (plastic to diesel, process engineered fuels, refuse-derived fuel, etc.), non-fossil fuel (hydrogen), construction materials (integration into road surfaces and cement) or just burning it for energy. The latter has generally been called ‘energy recovery’ though some propose this should rather be ‘thermal recycling’. In some instances, processing plastic waste into fossil fuel is proposed as ‘chemical recycling’. Clearly some of these approaches can be very polluting, support a linear economy, and do not sit easily within the concept of recycling. In nearly all cases, these phrases are created by the plastics industry or the waste management industry to project a ‘greener’ and more acceptable image of their polluting business models and activities.

Most of these applications will be discussed elsewhere in this brief. This section focuses on a technique that has been subject to significant media attention as a result of its recent promotion by corporate plastic product manufacturers and retailers – *chemical recycling*.

Chemical recycling of plastic waste is based on using chemical and thermal processes and techniques to break down and separate polymers to a level where they can be used again as monomers, polymers, or chemical feedstock in production of new polymers, or as feedstock for other chemical manufacture. The chemical recycling process seeks to remove impurities, contaminants, and additives from the plastic waste, resulting in ‘pure’ monomers (and sometimes polymers) for polymer feedstock. Some of the main challenges for chemical recycling to overcome are the ability to scale up to an industrial level, degradation of the polymers over time, decontamination of the feedstock, and very high energy use, as well as management of, and transparency about, emissions and residues.

There are currently many unanswered questions about the energy consumption, toxic emissions and residues, and practicality of the techniques that are considered to be chemical recycling. Chemical recycling is being heavily promoted by corporations who produce and sell plastic as part of their product line or in their packaging. The European Chemical Industry Council[20] argues that it differs from mechanical recycling in that it is able to process the large fraction of mixed contaminated plastic waste, remove contaminants, and either generate petrochemicals or separate monomers from contaminants to create polymers of similar quality to virgin polymers.

These petrochemicals can then be used either as 'feedstock', the chemical basis for polymers, or the monomers can be converted to polymer input for new plastic. However, degradation of monomers is still a problem with solvent recycling and chemical depolymerization. Thermal depolymerization can address degradation by generation of feedstock at the molecular rather than the monomer level (by pyrolysis or gasification), but historically the bulk of the output from gasification and pyrolysis processes is a form of reconstituted fossil fuel.

As pressure grows to ban plastics, the industry is seeking to update its campaign to focus consumers on recycling rather than impacts of plastic. The *Alliance to End Plastic Waste*[21] is a consortium of plastic production and consumer goods corporations who publicly promote chemical recycling and partner with technology start-ups and pilots using such techniques. There are many similarities between the current promotion of chemical recycling by the 'Alliance' as a 'solution' to global plastic pollution and the historical push to brand plastics as recyclable resin codes and the recycling symbol.

AS PRESSURE GROWS TO BAN PLASTICS, THE INDUSTRY IS SEEKING TO UPDATE ITS CAMPAIGN TO FOCUS CONSUMERS ON RECYCLING RATHER THAN IMPACTS OF PLASTIC.

While chemical recycling may supplement existing mechanical recycling rates, it has to be stated that it cannot be a 'solution' to the global plastic waste crisis while plastic production rises exponentially (Figure 1). Unless it can be implemented with high mandatory recycled content levels in new plastic alongside significant plastic production restrictions, chemical recycling will remain little more than window dressing for corporate promotional purposes. Further, chemical recycling for the purpose of creating reconstituted fossil fuels should not be supported as burning plastic-

---

[20] https://chemicalwatch.com/98760/guest-column-how-chemical-recycling-could-accelerate-safe-plastic-recycling-in-the-eu#overlay-strip

[21] https://endplasticwaste.org/en

derived fuels conflicts with the circular economy concept and exacerbates climate change.

CHEMICAL RECYCLING TECHNIQUES

The three main classes of chemical recycling techniques are:

1. **Chemical depolymerization:** a chemical-based process that converts plastic waste back into monomers using chemical reactions. It is suitable only for homogenous pre-sorted plastic waste streams such as PET, PU, PA, PLA, PC, PHA, and PEF.
2. **Solvent-based regeneration:** A purification process based on dissolving polymers in proprietary solvents, separating contaminants and reconstituting the target polymer. The process can accommodate a variety of plastics. The example of CreaSolv® in section 6 is a good example of this process.
3. **Thermal depolymerization and cracking (gasification and pyrolysis):** These processes heat plastic waste in a low-oxygen environment to produce molecules from mixed streams of monomers that then form the basis of feedstock for new plastic without degradation. The main output is syngas or synthesis gas.[22] Both gasification and pyrolysis have been trialed for decades to create energy (syngas burned to drive steam turbines) from municipal waste, but have not been a commercial success due to a combination of poor economics, high energy consumption requiring supplemental fuel, fires, explosions, emissions, and residues. These processes are also used to create 'plastic to fuels' (fossil fuels), as oils and diesel can be generated in addition to syngas. Figure 15 provides a flow chart showing the spectrum of mechanical, chemical, and solvent-based recycling applications.

Chemical depolymerization

This chemical recycling process is essentially the opposite of polymerization, described in figure 3, and produces single monomer molecules or shorter fragments called oligomers. The process only operates efficiently with highly selective inputs requiring careful source segregation and is well suited to PET and purified terephthalic acid (PTA) but is also applicable to PA, PU, PLA, PHA, PEF, and PC and a range of polyesters.

---

[22] Synthesis gas is a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and carbon dioxide with many trace contaminants. The name comes from its use as intermediates in creating synthetic natural gas (SNG) and for producing ammonia or methanol.

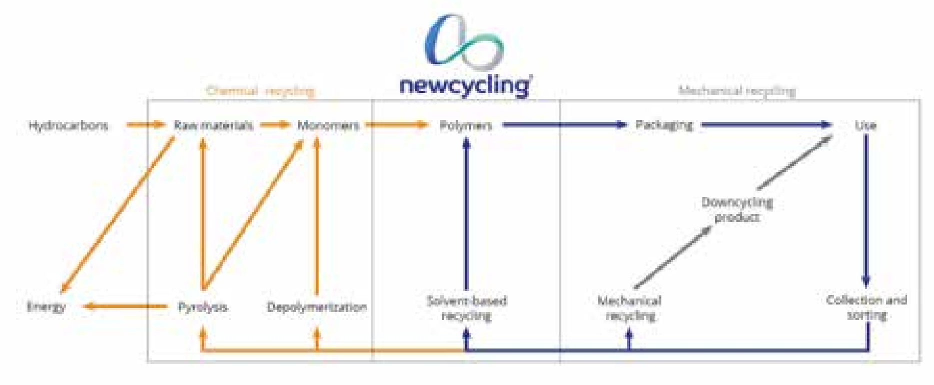


Figure 15. Spectrum of chemical recycling through solvent to mechanical recycling. Source: Newcycling®

Depolymerization produces monomers which must again be polymerized (additives must also be incorporated to replace those lost) to produce plastics, whereas solvent-based regeneration processes produce a purified polymer ready for conversion to plastic products. In both depolymerization and solvent regeneration, colorants, additives, and other contaminants can be completely separated at the molecular level (if processes are followed to strict standards), and the resulting output is of high purity (Crippa *et al.*, 2019). This level of purity is difficult to achieve with mechanical recycling unless a very clean input is used. Chemical depolymerization does not currently operate on a large-scale commercial basis, only industrial pilot plant and lab-scale operations exist. There has only been one large commercial-scale PVC solvent recycling plant (VinyLoop plant in Italy, a joint venture 10 000 tons/year facility,) operated since 2002, but it was shut down in 2018 because it could not economically separate the substantial amounts of phthalate plasticizers used in soft PVC to meet EU regulatory requirements (European Commission 2018).

AS WITH MOST CHEMICAL RECYCLING TECHNOLOGY THE TOXICITY, FATE, AND CHARACTERISTICS OF THE RESIDUES CREATED BY DECONTAMINATING THE MONOMERS HAS NOT BEEN MADE PUBLIC. THE HAZARDS ASSOCIATED WITH THE PROPRIETARY CATALYSTS USED IN DEPOLYMERIZATION HAVE NOT BEEN DISCLOSED.

Depolymerization allows the output monomers to be used separately or mixed to create virgin-grade polymers. PET is an example where the monomer output can be used flexibly and either applied to packaging or textiles (PET fibres in textiles are known as polyester). This could be a positive development, as most textile polymers are currently not recycled, yet make up 60% of the production use of PET, while the remaining volume is used mostly for packaging (Crippa *et al.*, 2019).

Given that PET accounts for 18% of global plastic production (Mouzakis, 2012), recycling PET textiles (less than 1% are currently recycled) and marine PET litter via depolymerization could potentially reduce this type of plastic pollution. Marine PET litter may have the added complication that it adsorbs and concentrates toxic POPs from ocean waters. Adsorption is the adhesion of molecules from a gas, liquid or dissolved solid to a surface. In this case to the surface of the PET plastic. If contaminated PET is then subject to depolymerisation the POP contaminants would be separated and form part of the toxic residue of the process generating more hazardous waste for disposal.

Energy use in depolymerization to cleave molecular chains and recover monomers depends on the target polymer. Currently energy use and other costs in this type of recycled polymer production are significantly higher than in virgin polymer production. However, the Global Warming Potential (GWP), a measurement of the carbon footprint of production, for plastics created via depolymerization is only around 60% of that of virgin plastics (Crippa *et al.*, 2019), which in time, may level the field in terms of cost structures – particularly if carbon pricing is implemented more widely. As with most chemical recycling technology the toxicity, fate, and characteristics of the residues created by decontaminating the monomers has not been made public. The hazards associated with the proprietary catalysts used in depolymerization have not been disclosed.

Solvent-based regeneration

Solvent-based purification and depolymerization results in high grade near-virgin polymer output. An example of a solvent regeneration technique, The CreaSolv® process, is discussed in terms of POPs contaminant separation in section 6. The solvent-regenerated polymer is ready to be converted directly to plastic product without the repolymerization steps required for monomers generated from depolymerization processes. Most contaminants, coloring agents, and other additives are removed at the molecular level without affecting the target polymer structure. However, further additives may be required to replicate the target product properties as they were with the original product.

Figure 16. Small plastic/foil packages known as sachets are common in low income countries. Photo: Isidro Castro

In general, the solvent-based purification works by dissolving the polymer in a specific solvent followed by the removal of contaminants such as additives, pigments, and non-intentionally added substances (NIAS) through filtration or phase extraction, and then precipitating the polymer using an anti-solvent in which the polymer is insoluble (Crippa *et al.,* 2019). Non-intentionally added substances have various sources and can be grouped into side products, breakdown products, and contaminants. Side products are often formed during the production of starting substances such as monomers and all further manufacturing stages. Breakdown products of structural elements of plastic food contact materials (FCMs), such as polymers and fibers as well as additives (e.g. antioxidants, UV-stabilizers), can also contaminate plastics as a NIAS (Bradley and Coulier 2007, Bignardi *et al.,* 2017).

While the process itself can regenerate near virgin quality polymers, the forward process of producing a product with extrusion, injection, or blow moulding can induce the same thermal and stress degradation as for any polymer. In this sense, solvent regeneration is not a perpetual plastic recycling process, as the mechanistic processes of plastic production would degrade the polymer after repeated cycles. Polyolefins such as PE and PP can be regenerated using high temperature and pressure. These are two of the highest volume production polymers, and solvent recycling could be applied to increase their recycling rate while removing contaminants (such as BFRs) for further treatment or destruction. Facilities have been established in the US, EU, and Indonesia at industrial pilot scale to recycle these plastics using solvent regeneration and to process multilayer packaging[23] including small sachets[24] used to package foodstuffs and cosmetics. Littered sachets are a major pollution problem in many countries with virtually no recycling options and little value to waste pickers.

While it may be technically possible to separate multilayer plastic packaging polymers, the viability and economics of scaling up remain unanswered. In the past, solvent recyclers using relatively homogenous input of PVC and PS found the viability of the process challenging with relatively simple inputs compared to complex mixed-layer packaging. Key challenges for solvent regeneration of complex plastic packaging include additional solvation and separation steps, time and energy required for solvent removal, the impact of residual solvent in polymer product, and the ability to recycle solvent contaminated with extracted additives (Kasier *et al.,* 2018).

Thermal depolymerization (pyrolysis and gasification)

The output of plastic pyrolysis and gasification cannot (with a couple of exceptions[25]) be used directly to produce polymers. The outputs are char, oil, tars, and gas with mixed hydrocarbon molecules containing a range of contaminants, which must be subject to much the same processes and refinement as crude oil requires before it can be developed into polymers. Therefore, these processes essentially generate raw hydrocarbon feedstock to manufacture polymers, rather than monomers or polymers directly. However, as mentioned previously, economic issues generally result in these raw hydrocarbons being sold and burned as a form of reconstituted fossil fuel made from plastic waste rather than being used as a new polymer or petrochemical feedstock.

Petrochemical and plastic corporations claim these technologies will take mixed plastic waste inputs with significant levels of contamination and produce new, clean feedstock for polymer production. The condensa-

---

[23] https://www.apk-ag.de/en/newcycling/

[24] In many low-income countries FMCGC market food products such as sauces, ketchup and cosmetics such as shampoo in very small foil/plastic sachets. The rationale is that poor consumers who can't afford larger containers of product are still being given the 'opportunity' to purchase these goods in small quantities.

[25] PMMA and PS waste can be subject to pyrolysis to produce monomers, but only with heterogenous feedstock and carefully controlled conditions.

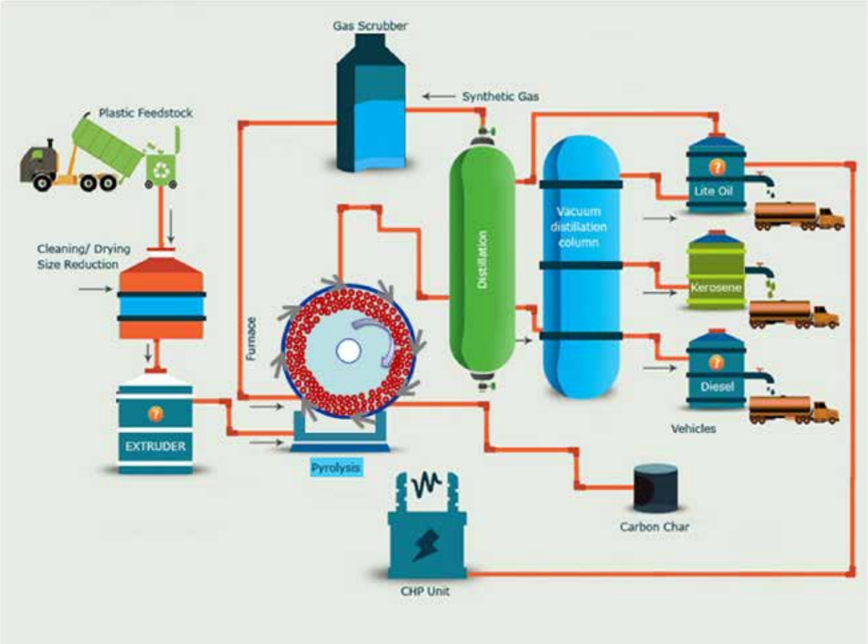


Figure 17. Plastic pyrolysis plant scheme with vortex reactor. Source: Ragaert and Delva 2017

tion on the syngas allows for separation of contaminants from the target outputs and concentrates them in the process residue. However, in reality syngas use in gas turbines has been restricted by contaminant levels in the past including halogens, fine particulates, sulfur, ammonia, chlorides, mercury, and other trace heavy metals.

Pyrolysis and gasification technologies have been around for decades, and have often been proposed as a technique for generating surplus 'green' energy from mixed municipal waste. Most commercial sized operations have failed to deliver commercially economic energy supplies. In Germany, the realization that this technology could not deliver excess energy beyond its parasitic loads cost the state dearly (Gleis 2012) after massive state investment in gasification of municipal waste for energy was lost due to facility failures and closure.

Industrial-scale pyrolysis has failed in the past, but new start-ups are reconfiguring the technology, which is still hampered by high energy consumption, up to 5-20% of the calorific value (Aguado *et al.*, 2003, Rollinson and Oladejo 2019) of the waste input. Mixed-plastic inputs to pyrolysis processes also have a significant potential for development of toxic polyaromatic hydrocarbons (PAHs) and dioxins. The most significant concern about scaling up pyrolysis is that

> *"there is significant uncertainty about whether building a pyrolysis infrastructure to recycle plastics will actually lead to new materials, or only to fuels. Such a linear lock-in is clearly not in line with the basic principles of a circular economy and is one of the major concerns when considering the role of pyrolysis in the plastics economy" (European Commission 2018).*

The basic principal behind the waste-to-energy version of these technologies is to heat waste in enclosed chambers in either no-oxygen (pyrolysis) or low-oxygen (gasification) environments to produce syngas (synthetic gas), which can then be burned to generate steam for electricity generating turbines. The key factor in commercial failure is an inability to generate surplus energy due to high external energy input required to heat the waste to pyrolytic temperatures. When energy consumption is calculated for the pre-sorting and drying of waste, the energy mass balance of pyrolysis is very poor.

Rollinson and Oladejo note in their seminal 2019 paper on the commercial failure of pyrolysis and gasification to generate meaningful energy balances from municipal waste that:

> *"Using literature review and case study methods, along with civil permit applications and experimental results, it shows that a pyrolysis plant for self-sustaining Energy from Waste is thermodynamically unproven, practically implausible, and environmentally unsound. A linkage between widespread commercial failures and a lack of focus on thermodynamic fundamentals is also identified, along with an environment of indifference or ignorance towards energy balances and sustainability when these technologies are presented, assessed and financed. The situation presents a high risk to investors and has the potential to adversely impact on societal transitions to a more sustainable future."*

Rollinson's criticism regards the high energy input and poor energy production characteristics of pyrolysis and gasification processing municipal solid waste (MSW) – including plastics – at anything other than small batch reactor scale. Thermal depolymerization of plastic by pyrolysis and gasification shares many of the shortcomings of the MSW processes, but also has differing outputs and objectives to MSW processing. When discussing plastic to fuel variations of 'depolymerization', i.e. when the output is to be combusted rather than recycled, Rollinson's criticisms can be applied more directly. This section addresses ‘depolymerization to plastic’ first and then ‘depolymerization to fuel’ in order to highlight these issues.

Depolymerization to plastic

Depolymerization using either pyrolysis or gasification breaks plastic down to simpler hydrocarbon compounds. In the low-oxygen environment polymers break down into small hydrocarbon molecules, which can be condensed from the hot gas. However, the molecule bond cleavage is more random, generating light hydrocarbon fractions and waxy fractions, which when condensed and combined, form an oily substance that can be used as fuel (Onwudili, Insura & Williams, 2009). In the case of carefully controlled conditions and feedstock both PMMA and PS monomers can be created from pyrolysis allowing for direct conversion to polymers. However, in general terms the output is a range of hydrocarbon fractions which can be used as feedstock for chemical manufacture, polymer production, or fuel, but must be subject to similar refining and production process as other petrochemical feedstock before it can be converted to final products.

While there are many proposals and trials to use pyrolysis and gasification to depolymerize plastics, the focus and promotion is on their ability to produce monomers for re-use with little consideration of associated health and environmental impacts. There is little to no information on the outputs of the pyrolysis or gasification process of plastics, such as toxic emissions, global warming potential, residues, and gas quality. However, certain inferences can be made about these factors based on the experience with pyrolysis and gasification of MSW.

THE KEY FACTOR IN COMMERCIAL FAILURE IS AN INABILITY TO GENERATE SURPLUS ENERGY DUE TO HIGH EXTERNAL ENERGY INPUT REQUIRED TO HEAT THE WASTE TO PYROLYTIC TEMPERATURES. WHEN ENERGY CONSUMPTION IS CALCULATED FOR THE PRE-SORTING AND DRYING OF WASTE, THE ENERGY MASS BALANCE OF PYROLYSIS IS VERY POOR.

Using mixed inputs of plastic waste has been demonstrated to generate toxic substances in char and emissions such as polyaromatic hydrocarbons (PAHs) and dioxins (Crippa *et al.*, 2019, Rollinson and Oladejo 2019). Researchers were able to “*quantify that the toxicity rating of PCDD/DF products from pyrolysis was three times the input at full operational* *performance and eleven times the input at pilot scale, and that these toxins were also present in both gas and oil*" (Chen *et al.*, 2014, cited in Rollinson and Oladejo 2019). Dioxin was found to be particularly problematic when chlorinated plastics such as PVC were included in the feedstock.

The implications are that entrained dioxin contamination (other POPs may also be present) in the output hydrocarbons will be carried through as contaminants into the final polymer products or fuel. They may also be released in emissions from the process, representing a health risk to workers and the community. The fate of the char material also becomes important, as char, being a carbonaceous material, is an ideal adsorption matrix for dioxins and other unintentionally created POPs. Indeed, activated carbon is injected into waste incinerators for the specific purpose of adsorbing dioxins from the flue gas (Mukherjee *et al.*, 2016).

Energy use of pyrolysis and gasification is very high. Pyrolysis operates at temperatures of around 300° – 600 °C, and gasification in the range of 1,200 °C – 1,500 °C. To heat the system to this level requires external sources of energy – usually sourced from fossil fuels. Some waste processing pyrolysis and gasification plants claim to be self-sustaining based on using the hydrocarbons (and char) they generate to power parasitic loads. However, as Rollinson and Oladejo note,

> *"Modest positive energy balances have been reported but only under the impractical and unsustainable conditions of:*
>
> 1. *When the drying energy has been set outside the system boundary.*
> 2. *Without considering fundamental (second law of thermodynamic) heat losses.*
> 3. *Discounting essential auxiliary energy to manage the plant such as, but not exclusively, gas cleaning, pre-processing, and supplementary fuels to the reactor."*

In other words, it is not plausible for these systems to be energy self-sufficient and generate energy or fuel as surplus, so their energy balance is therefore essentially negative.

Depolymerization using supercritical water oxidation (SCWO)

In most cases depolymerization of plastics is conducted by pyrolysis and gasification pathways (thermal depolymerization) or chemical depolymerization, both described above. Somewhat overlooked is the technology of plastic depolymerization using SCWO. While this technique is described later in the context of POPs-contaminated plastic destruction, it has also been modified for depolymerization.

Plastics that are developed via the condensation polymerization process including PET and nylon can be depolymerized to monomers relatively easily by supercritical waters or supercritical methanol. Cross-linked polymers can be subject to selective decrosslinking reactions in SCWO without significant loss of the backbone chains (Goto 2016). PET can be depolymerized to high-purity monomers at over 99% efficiency with either SCWO or supercritical methanol and both pilot and commercial plants have been developed.

Polyurethanes are produced through a reaction of polyisocyanate with polyalcohol (polyol). Tolylenediamine (TDA) and polyol can be produced from decomposition of polyurethane foam in subcritical water, corresponding to the initial isocyanate required for polyurethane production (Nagase *et al.,* 1998).

On this basis Kobe Steel, Ltd. (Japan) developed a supercritical water recycling process as far back as 1997, using subcritical water to convert heavy distillation residues of Tolylenediisocyanate (TDI) to TDA. The plant has operated at 10 tons/day since 1998. The TDI residues were normally incinerated, but this process allowed recovery of 99.5% pure TDA for polyurethane production (Goto 2016). A separate 20 tons per day-plant to process TDI by subcritical water was established in Korea in 2007 by Hanhwa Chemical (Adschiri *et al.,* 2011). In 2002, Panasonic also developed a process to recover and recycle high strength glass fiber-reinforced plastics (GFRPs) from GFRP waste using subcritical water hydrolysis. GFRP is a complex laminated composite material containing polyester resin with glass fibre and filler. Carbon fiber-reinforced plastics (CFRP) were also successfully recovered using similar processes.

Depolymerization using bacteria

While this technique is still largely at an experimental level, one company, Carbios, is scaling up and predicts it will have an industrial-scale facility within five years. The technique uses a bacterial hydrolase enzyme to reduce PET to monomers. The bacterial enzyme is based on a naturally occurring bacteria that has subsequently been modified by scientists to process PET more efficiently, claiming a 90% depolymerization within 10 hours (Tournier *et al.*, 2020). Carbios have teamed up with an enzyme production company, Novozymes, to scale up bacterial production using fungi to an industrial level.

This enzyme reportedly has a high efficiency producing 16.7 grams of terephthalate per liter per hour and the enzyme costs only 4% of the cost of virgin plastic made from oil. There still remain questions as to how the bacteria deal with additives and contaminants, and the hazardous nature of the waste stream generated after the PET has been removed from the plastic waste. The long lead time to commercial availability and the results of scaled-up trials may not reflect the early promise of the technique. Other bacterial approaches have been developed, including the use of Pseudomonas bacteria to decompose polyurethane (Espinosa *et al.*, 2020), and fungi that can break down PET, but all of these techniques appear to be years, if not decades, from any form of commercial activity.

Figure 18. TDI recycling via SCWO. Kobe Steel, Ltd. plant.
Source: Goto 2016

Figure 19. Panasonic pilot plant for FRP recovery.
Source: Goto 2016

3. PLASTIC TO FUELS

As plastic waste stockpiles grow at unprecedented rates around the world, many proponents are pushing for the adoption of fuels derived from plastic waste to 'substitute' for fossil fuels and to offset oil, gas, and coal extraction. The reality is that in all but a few cases the resulting product is fossil fuel or simply a repackaged form of plastic waste rebranded as a 'product' instead of a 'waste' for financial, regulatory, or subsidy purposes. One exception is the conversion of plastic waste to hydrogen, which is a clean burning fuel. But even with this example, the pathway to create hydrogen can involve energy-intensive processes that negate any net carbon footprint benefits. The following section discusses plastic to fossil fuel by depolymerization, plastic to non-fossil fuels (hydrogen), and the use of refuse-derived fuels (RDF) and associated products.

DEPOLYMERIZATION TO (FOSSIL) FUELS

The variability of mixed plastic waste feedstock, whichcan be used in pyrolysis and gasification, and the fuel-like output in terms of hydrocarbon feedstock, whichcan be generated with minimal post-processing, suggests that plastic to fuel will dominate this market sector. The creation of diesels, kerosene, and light oil —essentially fossil fuels for combustion—is currently the only viable market for pyrolysis output products from plastic waste processing. This creates the very real likelihood of 'linear lock-in' for plastic waste which would undermine circularity in the context of plastic waste chemical recycling (Crippa *et al.*, 2019).

Start-up companies using these techniques are in competition with the powerful petrochemical corporations for a share of the chemical/polymer feedstock market. These corporations have well established large-scale production capacities that allow for the production of very cheap feedstock. For the new start-ups, price-based competition will be considerable, and newcomers to the market are at an almost insurmountable disadvantage as low oil prices equate to low virgin plastic prices. Such pressures are likely to drive pyrolysis and gasification processors of plastic waste toward the more readily available market of plastic to fuel in the form of diesel for use by power plants and ships (Crippa *et al.*, 2019). In low- and medium-income countries this may also extend to vehicles.

Figure 20. Plastic to fossil fuel via pyrolysis.

The use of plastic to fuel has several serious implications for the circular economy, human health, and climate:

- **Linearity** – Apart from the calorific energy value recovered from plastic waste, the conversion of plastic to fossil fuels is essentially a direct road to resource destruction and maintains the petrochemical linear economic framework of extract – produce – dispose (combust). Adding an energy intensive pyrolytic step of converting petrochemical-based plastic back to petrochemical for combustion may well undermine the ultimate energy mass balance of the process (Rollinson and Oladejo 2019). With plastic production set to expand on a massive scale, it has to be questioned whether any real offset of virgin fossil fuel is occurring as a result of plastic to fuel implementation.
- **Toxic emissions** – There is evidence that pyrolysis generates and releases unintentional POPs such as dioxin and Conesa *et al.* (2008) note, "*The formation of PCDD/DFs is important in both combustion and pyrolysis processes. In pyrolysis, there can be a significant increase of congeners and/or an increase of the total toxicity due to the redistribution of the chlorine atoms to the most toxic congeners.*" The syngas from plastic waste pyrolysis has been found to be contaminated with a range of pollutants such as dioxins, PAHs, and tars, which make it difficult to use in combustion engines without further refinement (Rollinson and Oladejo 2019). The same contaminants impact the oils and char from pyrolysis. When these oil-like products are combusted, they release their contaminants. While pyrolysis operators may suggest their process emissions of dioxins are low, this is likely be at the cost of transferring such pollutants to the outputs of gas, oil, tar, and char. Indeed, "*researchers found that the toxicity rating of PCDD/DF products from pyrolysis was three times the input at full operational performance and eleven times the input at pilot scale, and that these toxins were also present in both gas and oil*" (Chen *et al.*, 2014, cited in Rollinson and Oladejo 2019). The entrained POPs and other

contaminants in the outputs are released directly to atmosphere on combustion.

- **Global Warming Potential** – The global warming potential of fossil fuels developed from pyrolysis of plastic cannot be ignored. For plastic products converted to fuels via pyrolysis, their time as a product can be regarded as a short pause in the linear process from their extraction as petrochemicals to their ultimate combustion as fossil fuels. However, in addition to the CO_2 that would normally be liberated by the combustion of the calorific fossil fuel content of the plastic, there is the additional 'embedded energy' of the original extraction, transport, and production of the plastic article to be considered. Further, there is the energy used to collect, sort, and separate the plastic to be fed to the pyrolysis unit as well as the energy used by the pyrolysis unit itself to generate the necessary heat for the process. Heating energy requirements for a pyrolysis process are very high. All considered, the global warming potential of fossil fuel derived from plastic is very high.

PLASTIC TO NON-FOSSIL FUELS (HYDROGEN)

Less attention has been paid to the conversion of plastic waste to hydrogen – a non-polluting, non-fossil fuel. A few industrial-scale pilot plants have been established to convert unrecyclable mixed plastic waste to hydrogen fuel. When hydrogen is used as a fuel in vehicles or stationary sources via a hydrogen fuel cell, the outputs are water and warm air. At face value the use of hydrogen fuel in a vehicle creates almost no carbon emissions compared to fossil fuels produced via refineries or derived from plastics. However, the method used to produce the hydrogen can significantly affect the overall global warming potential of the process. To denote the energy intensiveness of hydrogen production by different methods, the titles Green hydrogen, Blue hydrogen, and Grey hydrogen have been applied.

THE GLOBAL WARMING POTENTIAL OF FOSSIL FUEL DERIVED FROM PLASTIC IS VERY HIGH.

Green hydrogen is hydrogen produced via electrolysis using low-carbon renewable energy such as solar and wind power. Grey Hydrogen, accounting for around 98% of total hydrogen production today, is produced via steam methane reforming of natural gas in the petrochemical industry, without any attempt to offset carbon emissions, and represents a high-carbon pathway to producing hydrogen. Blue hydrogen involves the same

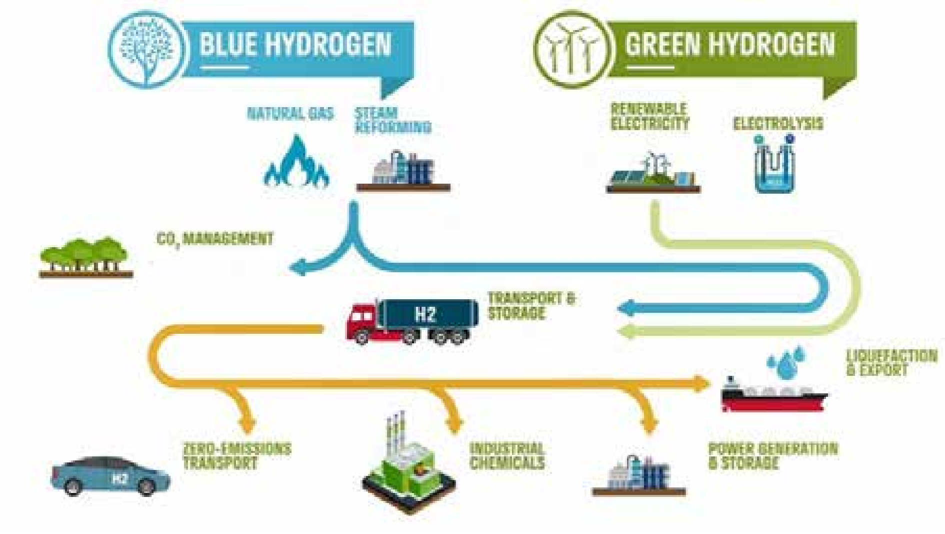


Figure 21. Green and blue hydrogen production pathways. Source: Woodside Petroleum.

petrochemical process (Figure 21), and is also a relatively high-carbon pathway to produce hydrogen, but is claimed to be cleaner as it involves the offset, capture, and storage or reuse of the carbon emissions.

The hydrogen economy is seen as key transition to a low-carbon future.[26] Vehicles, buildings (McClarty *et al.,* 2016), and even steel mills[27] can now be powered by hydrogen. However, this is largely dependent to the degree to which Green hydrogen can move from a minor to major supplier of hydrogen within the economy. Currently Grey and Blue hydrogen are much cheaper, but the price of Green hydrogen is expected to fall considerably over the next decade, while carbon pricing may force the price of Grey and Blue hydrogen higher.

Currently there are two pathways to generate hydrogen from plastic waste: pyrolysis and photoreformation.

Pyrolysis

Pyrolysis is used to convert the plastic waste to syngas, char, and tar. The syngas consists mostly of methane, carbon monoxide, and hydrogen. The

---

[26] https://www.iea.org/commentaries/the-clean-hydrogen-future-has-already-begun

[27] https://reneweconomy.com.au/another-nail-in-coals-coffin-german-steel-furnace-runs-on-renewable-hydrogen-in-world-first-55906/

hydrogen can then be isolated from the rest of the syngas components, which are combusted for energy. In essence, this is a different version of Grey hydrogen production.

This process suffers from linearity, emissions, and residues at the pyrolytic stage, and from a relatively high carbon footprint considering the embedded energy in creating the plastic, sorting and preparing it for pyrolysis, as well as the energy use in the pyrolysis plant to produce the hydrogen. However, it may represent a potentially sounder environmental outcome for unrecyclable plastic waste than incineration or dumping. It certainly represents a better outcome than pyrolysis producing fossil fuel. While the hydrogen may be a 'clean fuel' the methane and other constituents of the syngas (including contaminants such as dioxin) will still be combusted, posing similar problems as plastic to fossil fuel. Pilot plants are currently proposed to be established in the UK by PowerHouse Energy and Waste2tricity[28]. There is currently no industry established beyond these pilot proposals.

Photoreformation

Photoreformation is used to convert plastic waste to hydrogen. An emerging technology is being developed to generate hydrogen from unrecyclable plastic waste without the disadvantages of the pyrolysis process. Scientists in the UK have developed a system using cadmium sulfide quantum dots as photocatalysts to degrade plastics in the presence of sunlight and generate hydrogen. The process operates under ambient temperature and pressure, generates pure hydrogen, and converts the waste polymer into organic products such as formate, acetate, and pyruvate (Uekert *et al.*, 2018).

Annika Friberg of Chemistry World reports that,

> *"They drop the photocatalyst onto the plastic then immerse the plastic in an alkaline solution. Irradiation with sunlight reduces water from the solution to hydrogen while the plastic polymers simultaneously oxidize to small organic molecules. The group tested the system by photoreforming three common polymers; polylactic acid, polyethylene terephthalate and polyurethane. The results matched those of state-of-the-art hydrogen evolution photocatalysis systems that employed expensive sacrificial reagents."*

---

[28] https://www.rechargenews.com/transition/turning-plastic-waste-into-hydrogen-first-commercial-plant-moves-step-closer/2-1-733678

The process, as developed so far, operates efficiently irrespective of external organic contaminants on the plastic waste or embedded additives. While the technique is now in the process of a scale-up it has not yet been operated at pilot scale. While again it is essentially a linear process, it does have useful end-product chemicals, as well as hydrogen for energy. It could potentially be a simpler, less environmentally damaging way to manage large existing stockpiles of unrecyclable plastic waste, without the negative impacts of pyrolysis.

Source: © Moritz Kuehnel

Plastic waste is recycled to hydrogen using sunlight and a CdS photocatalyst

Figure 22. Photoreformation of plastic waste to hydrogen.

REFUSE-DERIVED FUELS (RDF) AND CEMENT KILNS

While RDF is not actually a form of chemical recycling, it is a form of plastic to fuel and has therefore been included at this point for comparative purposes.

Numerous terms have emerged to describe this ’product’, which is a repackaged, blended, or ‘engineered’ fuel made from plastic waste mixed with other elements of commercial, industrial, or municipal waste to be burned in cement kilns. Names include ‘Refuse-Derived Fuel’, ‘Alternative fuel’, ‘Process Engineered Fuel’, ’Secondary fuels’, ‘Substitute Fuels, ‘Solid Recovered Fuels’, Climafuel®, and so on. For convenience, they will hereafter be referred to as ‘RDF’.

According to The World Business Council for Sustainable Development these materials are:

> *“Selected waste and by-products with recoverable calorific value (that) can be used as fuels in a cement kiln, replacing a portion of conventional fossil fuels, like coal, if they meet strict specifications. Sometimes they can only be used after pre-processing to provide ‘tailor-made’ fuels for the cement process.”*

In reality, they are simply plastic waste, and municipal, commercial, and industrial waste processed and shaped into units based on calorific content for industry to burn. In other words, they are simply repackaged wastes and fossil fuels at an intermediary stage before combustion. Their combustion releases are similar to, if not identical to the toxic emissions, particulate, and climate change gases as they would be if burned in their 'loose mixed waste' form. The combustion of these products is not limited to cement kilns (though they consume the majority of such 'fuels'), but it is also burned in waste incinerators and some other specialized, boiler-based production industries.

The 'ingredients' of RDF generally consist of dry recyclable materials including:

- Timber
- Plastic
- Cardboard
- Paper
- Textiles
- MSW

The production of RDF usually involves reception of mixed waste which is subject to:

- Bag splitting/Shredding
- Size screening
- Magnetic separation
- Air classifier (density separation)
- Coarse shredding
- Refining separation by infrared separation
- Calorific content assessment
- Baling
- Pelletizing

The processing of waste into RDF is usually designed to remove inorganic materials (glass, metals, sand, stone, moist organics) and any other materials that inhibit combustion, and distribute the various waste streams within the finished product to homogenize the calorific content of the bale or pellets.

Figure 23. Baling and loading RDF in Ireland bound for Landskrona Energi Swedish Incinerator. Source: Geminor

Figure 24. RDF pellets. Source: Nexen Biomass

Proponents of RDF argue that it results in a net reduction of greenhouse gas (GHG) emissions from the cement kiln or incinerator as the RDF displaces fossil fuel. Typically, these arguments are based on comparisons to the waste being sent to landfill followed by high methane emissions (a potent GHG) instead of being processed to RDF. They never compare the results to the use of renewable energy to offset the fossil fuels as the results of RDF compare poorly. Burning mixed waste for energy as RDF in cement kilns or in waste incinerators, has the highest global warming potential per unit of energy generated compared even to other fossil fuels (see Figure 25), let alone renewables such as solar or wind power.

The difference between burning waste or burning RDF in cement kilns is largely a matter of semantics worth millions of dollars to the producers of RDF and the cement kilns who use it. The contortions of language involved in trying to pretend that RDF (and its namesakes) are anything but waste came to light recently when the Philippines investigated RDF shipments from ResourceCo in Australia to Holcim Cement in the Philippines.[29]

With diplomatic tensions between Canada and the Philippines at breaking point over Canada's failure to retrieve hundreds of illegally shipped waste containers (including threats of war)[30], heightened scrutiny of shipping containers exposed shipments of waste classified as RDF from Australia.[31]

The ensuing furore saw port officials questioning the labelling of the shipment,*"The question is, are they the same? They insist it is. But I beg to disagree because garbage is garbage, fuel is fuel."* At a subsequent media briefing, Presidential Spokesperson Salvador Panelo said, "*We will not allow ourselves to be dumping ground of trash."* Complicating the issue, the Environment Department said the shipment was legal because it was RDF bound for Holcim Philippines cement kilns.

The definitional arguments continue and are complicated by the Basel Convention and the newly operational Basel Ban Amendment[32] which prohibits member states of the OECD and the European Union and Liechtenstein (Annex VII countries) from shipping hazardous waste, as defined by the treaty, to non-Annex VII countries[33]—generally countries with low to medium income that cannot manage such wastes in an environmentally sound manner. Under certain conditions, the Basel Convention allows the country of import to determine whether a shipment of certain material is considered a 'hazardous' waste, and to reject the shipment. This would depend on the contents and concentration of materials that may be hazardous within the RDF or PEF.

The rise of RDF is attributable to its profitable nature. Not only can the producer of RDF charge industry and local government for the waste it receives, they can also charge the recipient of the RDF (e.g. cement kilns). Along the way, they can also profit from the monetary value of the biomass fraction of the RDF under various greenhouse gas protocols, such as the European Union Emissions Trading Scheme[35], the UK Renewable

---

[29] https://cnnphilippines.com/news/2019/5/23/denr-emb-customs-fuel-holcim-australia-mismis-oriental.html

[30] https://www.thetimes.co.uk/article/duterte-threatens-war-against-canada-over-dumped-rubbish-tbmsdj3nx

[31] https://cnnphilippines.com/news/2019/5/23/denr-emb-customs-fuel-holcim-australia-mismis-oriental.html

[32] http://wiki.ban.org/The_Basel_Ban:_A_Triumph_Over_Business-As-Usual

[33] https://ipen.org/documents/basel-ban-amendment-guide

[34] U.S. Environmental Protection Agency, Emissions & Generation Resource Integrated Database, eGRID Version 1.0, 9th Edition, (2010 data), released February 24, 2014. http://www.epa.gov/egrid/ Data summarized and analysed by Energy Justice Network here: http://www.energyjustice.net/egrid

[35] https://ec.europa.eu/clima/policies/ets_en

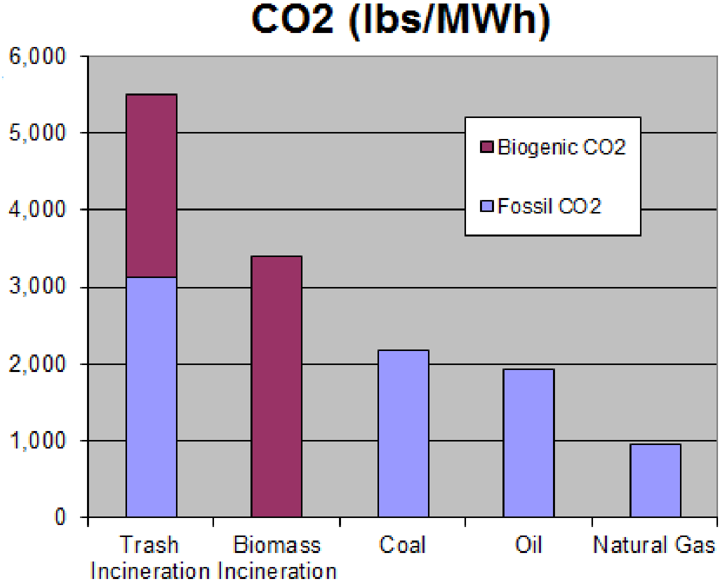


Figure 25. CO_2 emissions of burning waste compared to other fuels per MWh.
Source: US EPA[35]

Obligation Certificate[36], and the Australian Emissions Reduction Fund.[37] The biomass fraction such as paper, cardboard, and wood are considered to generate renewable energy, although studies have effectively debunked this carbon accounting proposition (Haberl *et al.*, 2012, Searchinger 2010).

In their search for high calorific value fuels, cement kilns still have to limit their use of waste plastics due to the corrosive effects of the thermal degradation products. Hahladakis *et al.* (2018) note, *"Halogens emitted from the combustion of plastic waste can also cause corrosion in incinerators and other thermal facilities. Chlorine and bromine may accumulate in cement kiln systems limiting their capacity for thermal recovery of plastic."*

Of more concern for the environment and human health are the implications of the cement kilns not operating to BAT BEP standards when using halogenated (bromine, chlorine, fluorine) plastic as fuel. *"However, uncon-*

---

[36] https://www.ofgem.gov.uk/environmental-programmes/ro/about-ro
[37] https://www.environment.gov.au/climate-change/government/emissions-reduction-fund

trolled combustion of plastic waste and, in particular of those containing halogens such as, PVC, polytetrafluorethylene/teflon, plastic containing brominated flame retardants, etc. can cause emissions of hazardous substances, e.g. acid gases and unintentional persistent organic pollutants (POPs) such as dioxins" (Hahladakis *et al.*, 2018).

Cement kilns burning traditional fossil fuels have less risk of these types of toxic emissions, but including mixed plastic waste rebranded as RDF only increases these risks – particular for countries who do not have the emission monitoring, enforcement, and monitoring provisions required to operate cement kilns to European BAT BEP standards.

In conclusion, RDF is simply rebranding of waste as a product to attract climate mitigation subsidies at the expense of real renewable energy, avoid waste trade restrictions, and make a profit from transferring the waste burden of wealthy countries to those countries least able to manage it.

CHEMICAL RECYCLING CONCLUSION

The plastic chemical recycling processes are emerging technologies that are almost entirely at pilot stage with the exception of some SCWO technologies. Corporations who sell large volumes of plastic in the form of products and packaging, such as BASF[38], Unilever[39], Proctor and Gamble[40], Mitsubishi Chemical Corporation[41], Dow Chemical[42], Chevron Phillips Chemical Company LLC [43], and others, are partnering with or acquiring engineering start-ups, established chemical recycling companies, and technologies to focus on conversion of plastic waste to plastic or chemical feedstock. Fast-Moving Consumer Goods companies (FMCGC) have generated extensive media about their attempts to engage chemical recycling as a solution to the plastic pollution issue, distracting the public and policymakers from the environmental impacts of plastic. Chemical recycling is also the centerpiece of solutions proposed by The Alliance to End Plastic Waste[44], a cynically named consortium of companies such as Dow Chemical, DSM, ExxonMobil, Formosa Plastics Corporation, and many other petrochemical and FMCGC who produce the petrochemicals and plastics at the heart of the pollution problem.

---

[38] https://www.basf.com/global/en/who-we-are/sustainability/whats-new/sustainability-news/2019/basf-invests-in-quantafuel.html

[39] https://www.unilever.com/news/news-and-features/Feature-article/2018/our-solution-for-recycling-plastic-sachets-takes-another-step-forward.html

[40] https://purecycletech.com/2019/09/successful-run-of-feedstock-evaluation-unit/

[41] https://www.hydrocarbonengineering.com/petrochemicals/26022020/mitsubishi-chemical-acquires-chemical-recycling-companies/

[42] https://recyclinginternational.com/plastics/dow-signs-up-to-chemical-recycling/27557/

[43] https://www.chron.com/business/energy/article/Chevron-Phillips-subsidiary-launches-chemical-13810002.php

[44] https://endplasticwaste.org/

As an example, Coca-Cola has engaged in agreements with Ioniqa[45], which has recently commissioned a 10,000 tpa plant in the Netherlands, and with Loop industries[46] to access depolymerized, recycled PET content for their packaging. Loop Industries, Inc., depolymerize PET plastic and polyester fiber, plastic bottles, packaging, carpets, and textiles, as well as ocean plastics that have been degraded by the sun and salt. The Loop system reduces PET waste to its monomers Dimethyl Terephthalate (DMT) and Monoethylene Glycol (MEG) under low heat at atmospheric pressure.[47]

Rather than limiting the exponential growth in plastics production, the use of chemical recycling is seen by large petrochemical corporates as a means to continue with business as usual, while “chemical recycling processes can count towards recycling targets”[48]. The aim is not reducing plastics production, it is minimalistic regulatory compliance and a marketing strategy to avoid plastic bans.

Chemical recycling can conserve resources and perhaps recycle some forms of plastic scrap that mechanical recycling cannot (such as contaminated and mixed polymers). This effort may contribute in a marginal way to the circular economy, but there are many questions about scale-up, energy intensity, pollution, and residues that cannot be answered for lack of industry data. However, there is enough information around techniques like pyrolysis to suggest there will be significant problems, and the concept of chemical/solvent ‘purification’ suggests that contaminated residue will be a significant hazardous output of these processes.

But in the end, no amount of chemical recycling (or mechanical recycling) will fundamentally resolve the plastic pollution issue, while petrochemical plastic production rates skyrocket in a supply-driven attempt to pivot petrochemical companies away from carbon liabilities in fossil fuels. As long as petrochemical corporations see plastic production as a safe haven to maintain extraction and production of petrochemicals, then plastic pollution will continue to blight the planet. Until global regulation can minimize plastic production within ecologically sustainable limits with high corresponding rates of mechanical and chemical recycling, then chemical recycling will remain a public relations distraction.

---

[45] https://www.ptonline.com/news/coca-cola-invests-in-pet-recycling-initiatives-

[46] https://www.ptonline.com/articles/loop-industries-to-supply-100-recycled-pet-to-coca-cola-bottlers-

[47] https://www.loopindustries.com/en/tech

[48] BASF (2019) ‘BASF invests in Quantafuel to jointly drive chemical recycling of mixed plastic waste.’ https://www.basf.com/global/en/who-we-are/sustainability/whats-new/sustainability-news/2019/basf-invests-in-quantafuel.html

4. MECHANICAL RECYCLING

Mechanical recycling uses only mechanical methods to reprocess plastic waste and this typically involves grinding, washing, separating, drying, re-granulating, and compounding (Ragaert *et al.,* 2014). The recyclates from these processes can be used to replace virgin polymers in the production of new plastic articles. For thermoplastics, after remelting the recyclate can be processed by injection or rotational moulding, extrusion, and heat pressing (Lettieri and Baeyens 2009). These techniques are not applicable to thermoset plastics, which will not remelt.

Mechanical recycling of plastic waste is a mature, well-established industry that operates well below its capacity due to a range of technical, financial, and policy challenges. In the EU, in 2016, 8.4 million tons of plastic were recycled, but 11.3 million tons were burned in incinerators, while around 7.4 million tons were landfilled (Delva *et al.,* 2019).

Among these challenges, the following have proven difficult for the industry to overcome. At a technical level, many plastics have become more complex, multi-layered and contain many additives (including toxic additives) that preclude or inhibit the ability of mechanical recyclers to process or sell them. Competition from cheap, virgin-production plastics using petrochemicals is so great that the volume and scale required to collect, clean, and process waste plastics limits the market for plastic recyclate. Waste incineration in some regions and countries (EU, Japan, Scandinavia, and the US) competes for supplies of recyclable plastic.

Policy makers in most countries have not yet moved to mandatory recycled plastic content in products or to government procurement policies in order to drive demand for recycled plastic, support a circular economy, and provide a significant boost to investment in plastic recycling. The over-reliance on a waste export model by many developed countries has left their domestic recycling infrastructure undeveloped, with insufficient investment and little domestic demand. Australia is an example of a country that relied heavily on plastic waste exports to China, while neglecting its domestic recycling infrastructure only to find itself in a crisis when China's National Sword policy was implemented.[49] Many countries have relied on export of low value plastic waste from high-income to low- and middle-income countries that recycle some of the waste while the rest

---

[49] https://www.abc.net.au/news/2019-01-11/australias-recycling-crisis-one-year-on-whats-changed/10701418

is burned or dumped in the environment contaminating the food chain (IPEN, Nexus 3, Ecoton, 2019). Such exports diminish the need for the establishment of domestic mechanical recycling industries for plastic waste in many high-income countries.

KEY TECHNICAL PROCESSES

Collection

For an efficient and profitable mechanical plastic recycling system, source separation and collection systems from the public, commercial, and industrial sources is very important. These should be supplemented with targeted collection schemes from agricultural, automotive, and Waste Electrical and Electronic Equipment (WEEE) sources.[50] The main collection methods used in many developed countries are curbside collection, drop-off locations, buy-back, and deposit-refund programs. These focus on plastic packaging and consumer products. Industrial waste plastics (cut offs and scraps) sourced directly from factories can be particularly valuable due to lack of contamination from comingling with organic wastes. The cleaner the incoming plastic waste, the less resource-intensive is the cleaning phase. In low-income countries, the collection, sorting, and cleaning processes are less sophisticated and have high risks for workers, but can also be very efficient (see section 1).

Sorting and cleaning

Mixed plastics mostly arrive at the mechanical recycling facility contaminated with organic matter and other materials, and must be sorted, separated, and cleaned to facilitate mechanical recycling. The first step is the removal of non-plastic materials such as metal, wood, and paper. Shredding may occur during the nest steps to facilitate separation. The separation of rigid plastics from non-rigid plastics (such as chip packets and foils) is followed by division into colored and clear plastics. Finally, polymer types have to be separated into different fractions. Metals can be removed by magnets and eddy currents. Non-rigid plastics can be separated by blowers and wind sifters. Color separation is conducted by optical color recognition sensors (Delva *et al.,* 2019).

---

[50] While it is important to collect plastics from these sources, great care should be taken to ensure that they are assessed for POPs content. Significant fractions of WEEE and automotive plastics have added brominated flame retardants, which can contaminate non-brominated polymers during the processing of creating polymer recyclate.

Polymer Sorting

Mixed polymers decrease the value of recyclate and contribute to degradation of strength and other properties of the final products or cause difficulties in processing due to different melting temperatures. Polymer sorting is conducted by direct and indirect methods. Direct methods include density separation (Figure 30), but for mono separation, more advanced techniques may be necessary due to density overlap such as flotation or froth flotation (Burat *et al.,* 2009), use of centrifuges, or hydrocyclones (Pascoe, 2006). Indirect methods involve the use of optical scanners to detect and separate polymer types. The most commonly used technology is the FT-NIR (Fourier Transform Near-Infrared) sensor, but it can falsely detect black plastics and contaminants. The sensor field is developing rapidly, and black plastic sensors and PVC-sensing equipment is now in use (see Figures 27, 28 and 29). The introduction of bioplastics has also recently raised concern about contamination of the recycling chain and potential incompatibility with fossil fuel-based polymers (Alaerts *et al.,* 2018).

Remelting and extrusion

The sorted, cleaned, and shredded polymers may then be subject to remelting (except thermoset plastics) and extrusion, where they are formed into bulk pellets (nurdles) to be sold to plastic product manufacturers. With some polymers such as PET, solid-state polycondensation (SSP) within a vacuum is applied at specific temperatures (180–240 °C), causing post-consumer contaminants to rise to the surface of the PET and to be removed by the vacuum force (Cruze and Zanin 2006).

TOXIC ADDITIVES CHALLENGE MECHANICAL AND CHEMICAL RECYCLING.

Numerous institutional, economic, and policy challenges for recycling have already been mentioned in this report, but there are also technical challenges related to the complexity of post-consumer polymeric materials, and their separation and processing. Thermodegradation of polymers in the recycling process due to heat and mechanical sheer is a significant problem (Delva *et al.,* 2019). Before reaching the recycling facility the waste plastic may have undergone other forms of degradation such as heat, light, oxygen, and moisture exposure (Ragaert 2016), which can also degrade the output recyclate product.

A second challenge is the immiscibility of the main high-volume polymers in the remelting phase, leading to subsequent degradation of the final recyclate product. Recyclers attempt to segregate mono-streams as much as is practical in order to minimize the degradation of the end product. No mechanical recycling process has been able to achieve 100% contamination free mono-streams, but very low cross-polymer contamination levels are frequently achieved (Delva *et al.*, 2019).

The third major technical challenge is the management of additives. As described in section 1, the widespread use of chemical additives in plastics to impart specific characteristics leads to significant problems in chemical and mechanical recycling. For most forms of mechanical recycling, toxic chemical additives, their degradation products, and even 'side products' are carried through the recycling chain and into the plastic recyclate destined for inclusion in new plastic products.

Side products can include contaminants entrained in the additive during its manufacturing process. An example is highly toxic brominated dioxins that are formed during the manufacture of BFRs which then 'follow' the BFRs into polymers when BFRs are added to final plastic products (Watson *et al.*, 2010). The brominated dioxins can then be detected not only in the final BFR-added product, but also as it moves along with the shredded plastic in the mechanical recycling phase, and then into new products using plastic recyclate (Petrlik *et al.*, 2018), and even into the environment following disposal.

VIRGIN PLASTIC PRODUCERS UNLOAD THE COST OF EXTERNALITIES ASSOCIATED WITH THEIR PRODUCTS ONTO THE MECHANICAL RECYCLING SECTOR. THE ADDITION OF TOXIC AND INCOMPATIBLE ADDITIVES TO POLYMERS AT PRODUCTION STAGE REPRESENTS COSTLY CHALLENGES TO DOWNSTREAM MECHANICAL RECYCLERS THAT REDUCES THEIR ECONOMIC VIABILITY.

Mechanical recycling workers are particularly vulnerable during shredding and extrusion phases of polymers. The temperature for extrusion of plastic lies within the dioxin formation and release range (Hahladakis *et al.*, 2018). Other toxic substances and endocrine disrupting chemicals (EDCs) can be released at this point leading to exposure including metals, volatile organic compounds (VOCs), phthalates, polycyclic aromatic hydrocarbons (PAHs), PBDEs (polybrominated diphenyl ether), polyamide-epichlorohydrin (PAE), polybrominated dibenzo-p-dioxins, and furans (PBDD/F) (Tang *et al*,. 2014, Huang *et al.*, 2013).

Chemical recycling workers may also be subject to exposures from volatile gases and fugitive particulate from toxic additives during the processing phase whether using solvents, heating in pyrolysis plants, pre-treating plastic waste for processing, or handling the toxic residues from chemical recycling.

Mechanical recycling represents a useful contribution to the overall objective of a circular economy but in the face of exponential increases in very cheap, virgin plastic production does not represent a solution to the current plastic pollution paradigm. Virgin plastic producers unload the cost of externalities associated with their products onto the mechanical recycling sector. The addition of toxic and incompatible additives to polymers at production stage represents costly challenges to downstream mechanical recyclers that reduces their economic viability.

Holding virgin plastic producers accountable for their additives (toxic or otherwise) and unrecyclable products (complex laminates etc.) by regulation, taxes, or other policy and market instruments is necessary for mechanical recycling to adopt a meaningful position in the circular economy. These measures would also have considerable human health and environmental benefits from exposure reduction. Such measures can be implemented immediately but are still not enough. Ultimately freezing or reducing current production levels for plastics, while mandating recycled polymer content, is the essential pre-requisite to move to a circular economy for plastics.

DOWNCYCLING

A common problem associated with mechanical recycling is the degradation and mixing of polymers leading to loss of the characteristics that made the initial pre-recycled polymer desirable. As the plastic qualities are degraded through the recycling process, some may not be able to be returned as input to new plastics, and are used to create less valuable, limited application, plastic products.

Some examples include:

- park benches
- plastic lumber poles for gardens
- drainage pipes
- carpets
- railroad ties
- truck bed liners
- plastic roads

Most of these products have lost so many structural characteristics that they cannot be subject to recycling again after they have reached this point. It is not clear if chemical recycling can be applied to these downcycled products in an effort to recover monomers or polymers.

Concerns have been raised over recent projects attempting to integrate plastic waste into road surfaces as a means of downcycling. The roads are expected to last 4-6 years (Hahladakis *et al.*, 2018) before deterioration, and it is not clear how the material from maintenance or demolition will be managed. Very few studies have attempted to examine the environmental and human health implications of blending plastic waste into bitumen or paving using only melted plastics.

Some of the concerns include:

- Perpetuating a linear extraction-production-disposal cycle for plastics that 'hides' the waste.
- Risk to road workers from inhaling toxic emissions from the melted plastic during construction, including chlorinated and brominated dioxins (from PVC and brominated flame retarded plastic respectively).
- Risk to road workers from inhaling other gases from melted plastics such as PP, PS, or PE during construction, including especially carbon monoxide, acrolein, formic acid, acetone, formaldehyde, acetaldehyde, toluene, and ethylbenzene, as well as from the vast array of additives incorporated into the plastics such as phthalates.
- The release of chemical additives and microplastics into the environment from a combination of weathering and abrasion from vehicle tires and the subsequent impact on the environment.

When downcycling plastic waste via shredding and extrusion into lower-value products and uses, there is also a significant risk to workers engaged in the manufacturing process, where heating of the waste releases volatile compounds or particulates (and this may also apply to plastic road construction workers). The processes of shredding and heating can endanger workers from exposure to emissions such as dioxins, phthalates, and VOCs, but also to particulate-adsorbed monomers with toxic characteristics, such as Bisphenol A (BPA), styrene, and vinyl chloride monomers.

5. MANAGEMENT OF POPs-CONTAMINATED PLASTIC

Plastics that are contaminated with persistent organic pollutants (POPs) because they have been deliberately added to impart a property to the plastic (fire retardancy, etc.), or because they have been inadvertently added because the POP is a trace contaminant of another additive, or because the plastic in its waste form has become contaminated by POPs (as is the case for some marine plastic litter), in most cases need to be considered separately from most other forms of plastic waste. The Stockholm Convention on Persistent Organic Pollutants requires all parties to destroy or irreversibly transform POPs waste (including POPs-contaminated plastic) so that it no longer exhibits POPs characteristics. These characteristics include toxicity in tiny amounts, persistence in the environment, ability to travel long distances, and bioaccumulation in fatty tissues of living organisms causing food chain contamination.

To be defined as POPs waste and subject to Stockholm Convention Article 6 measures, the plastic must contain one or more POPs that for each POP exceeds a prescribed concentration level known as the Low POP Content Level (LPCL). These levels are reviewed periodically, and are sometimes reduced as science demonstrates that POPs are harmful at lower levels than previously understood. So, if a piece of plastic contains a POP or a mixture of POPs at a concentration exceeding the LPCL, it must be destroyed and not recycled, unless the POP can be removed and managed separately (there are some cases where this is possible).

WHY MUST POPS-CONTAMINATED PLASTIC BE DESTROYED AND NOT RECYCLED?

Plastics contaminated with POPs should not be recycled. The Stockholm Convention prohibits the recycling of POPs waste to prevent the highly toxic chemicals from entering other products and causing unintended and dangerous exposures. However, from time to time, under political pressure, the Convention has granted time-limited exemptions to allow the recycling of materials contaminated with some POPs, such as the brominated flame retardants, commercial PentaBDE and commercial OctaBDE. In January 2020, the European Union announced it will revoke its exemption for recycling of plastics and other materials containing polybrominated diphenyl ethers (PBDE), a brominated flame retardant used widely in plastics. The exemption to allow recycling of this POP has proven to be a costly mistake.

Studies conducted by IPEN have demonstrated that plastic contaminated with PBDEs (usually from electronic waste and automotive plastics) has bled into the recycling chain of non-contaminated plastics. As a result, consumer goods with high exposure potential, such as children's toys and cooking utensils, manufactured from recycled plastic have been found to contain elevated levels of these POPs. Other POPs are also entering the plastic recycling chain contaminating goods made from recycled plastic with short-chained chlorinated paraffins (SCCPs)[51], dioxins, brominated dioxins[52], hexabromocyclododecane (HBCD), and other highly toxic POPs chemicals.

The ongoing contamination of the plastic recycling chain with highly toxic persistent organic pollutants threatens to poison the circular economy before it emerges from its infancy. So before any discussion about the relative merits of different 'solutions' to end-of-life plastic waste takes place, it must be acknowledged that POPs-contaminated plastic must be identified and removed from the general recycling system, then destroyed or treated in such a way that POPs are removed or so that the plastic exhibits no POPs characteristics[53], thereby allowing the remaining polymer to be recycled by other means. There are some very limited examples where POPs can be removed or separated (such as solvent regeneration and SCWO). The rest of POPs-contaminated plastic must be destroyed in the most environmentally sound manner, according to Convention guidelines.

TECHNIQUES FOR THE ENVIRONMENTALLY SOUND MANAGEMENT OF POPS-CONTAMINATED PLASTICS

This section only considers environmentally sound technologies for destruction of POPs-contaminated plastic, and a few specific technologies where the POPs can be separated from the plastic and allow recycling of the remaining polymer.

One of the requirements of environmentally sound technology is that it destroys or irreversibly transforms POPs without unintentionally generating further POPs in the process. Unintentional POPs or UPOPs are the by-products of combustion technologies where waste chlorine and carbon are among the feedstock (the precursor formation pathway) and *de novo* synthesis where polychlorodibenzo-p-dioxins (PCDD) and polychlorod-

---

[51] https://ipen.org/sites/default/files/documents/ipen-sccps-report-v1_5-en.pdf

[52] https://ipen.org/documents/toxic-soup-dioxins-plastic-toys

[53] This is a requirement of Article 6 of the Stockholm Convention.

ibenzofurans (PCDF), known commonly as dioxins and furans, form in the post-combustion phase. The Stockholm Convention lists UPOPs in Annexes C, Part I to the Stockholm Convention:

- Hexachlorobenzene (HCB);
- Hexachlorobutadiene (HCBD)
- Pentachlorobenzene (PeCB);
- Polychlorinated biphenyls (PCB);
- Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/ PCDF); and
- Polychlorinated naphthalenes (PCN).

Combustion and other incineration processes, such as waste to energy incinerators, pyrolysis, gasification, cement kilns, metallurgy blast furnaces, and plasma arc units, have a strong tendency to form UPOPs in emissions and in residues from their filters such as fly ash, cement kiln dust (CKD), bottom ash, and scrubber water effluent where wet scrubbers are engaged to strip flue gases. IPEN does not regard these technologies as environmentally sound due to their propensity to generate highly hazardous UPOPs[54], thereby perpetuating the POPs-contamination cycle. These technologies are not discussed further in this report for treatment of POPs-contaminated plastics.

SEPARATION OF POPs-CONTAMINATED PLASTIC WASTES FROM OTHER POLYMERS

Managing POPs-contaminated plastic waste in an economically efficient manner requires the separation from non-impacted waste. This presents some challenges, as testing for POPs can be complex and expensive in the general absence of labelling of plastics containing POPs additives. For example, hard casings (High Impact Polystyrenes - HIPs) for computers and electrical products are likely to contain brominated flame retardants that have been identified as octa-BDE, penta-BDE, and deca-BDE subsets of the PBDE group. POPs such as SCCPs are used as plasticizers in different types of plastics, but especially PVC. However, some techniques have been developed to simplify identification.

Some electronic screening methods have been developed to separate brominated POPs-contaminated plastics from other polymers including imaging and XRF technology.

---

[54] See Annex C Stockholm Convention on Persistent Organic Pollutants http://chm.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx

Mixed PP/PE fraction

Figure 26. Unisort Blackeye by Steinert for separation of brominated black plastics. Source: Steinert Global

One type of imaging equipment that can sort plastic by type of polymer (including black plastic) is *UniSort BlackEye from STEINERT.*[55] The UniSort BlackEye uses hyper spectral imaging (HSI) technology.

The UniSort BlackEye sorts black plastics such as PE, PP, PVC, and styrenes, and recovers recyclates from materials that were previously sent for processes like thermal recovery.

XRF (X-RAY FLUORESCENCE) SEPARATION

The use of XRF to detect materials on the basis of chemical composition is an effective method to screen brominated flame retardants in plastics, but may also have application for fluorinated plastics in the future due to the ability of XRF to detect halogenated elements, such as bromine, chlorine, and fluorine. One example of this application for separation of brominated plastics is the Redwave company.[56] They have incorporated an XRF-based sensing technology into a conveyor belt, and separation technology for mass screening of plastics to separate outputs into brominated and bromine-free plastics.

An alternative to fixed separation systems includes hand-held XRF devices that may be applied to screening of incoming plastic batches for recycling that are suspected of brominated POPs contamination. They can also be used to detect potential brominated POPs-contamination of surfaces in recycling and plastics processing centers where brominated plastics have been handled. Portable XRF devices can be calibrated to detect and measure a range of elements including bromine and chlorine. An example of this widely available device is produced by Olympus[57] (who

---

[55] https://steinertglobal.com/au/magnets-sensor-sorting-units/sensor-sorting/nir-sorting-systems/unisort-blackeye/

[56] http://www.redwave-us.com/recycling-solutions/plastics/

[57] https://www.olympus-ims.com/en/innovx-xrf-xrd/

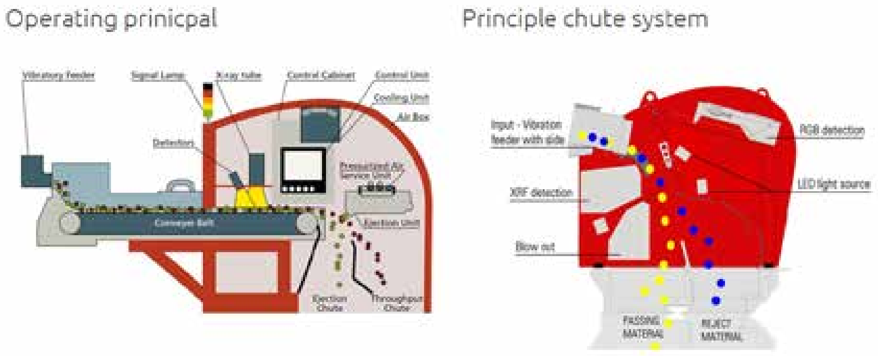


Figure 27. Redwave XRF-based plastic separator. Source: Redwave Austria

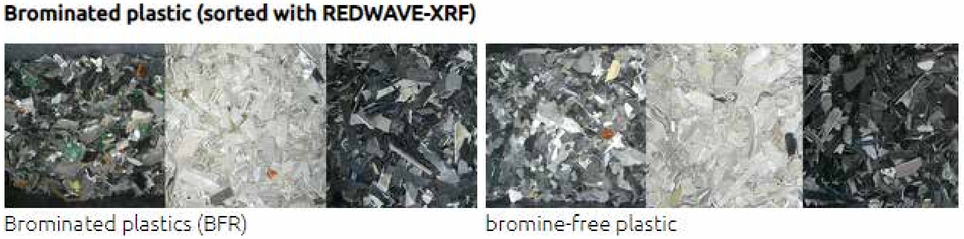


Figure 28. Post-separation plastics divided into brominated and non-brominated plastic using the Redwave XRF system. Source: Redwave Austria

also partner with Redwave on component supplies for fixed systems), and is designed for testing consumer goods, analysing metals and alloys, and surface contamination by elements such as lead and mercury.

IPEN uses this device for screening of plastics and consumer goods (including children's toys) suspected of contamination with brominated POPs as a result of being produced from recycled plastics where PBDEs have entered the recycling chain. Subsequent laboratory analysis of those articles identified as contaminated can then produce a lower quantification limit and differentiate individual BFR congeners, if required, for additional quality assurance. The XRF device can be a cost-effective screening method of excluding non-impacted articles instead of using more expensive laboratory analysis on each item.

Regulatory Compliance Concentration Limits

Element / Regulation	RoHS/ WEEE	Consumer/ CPSIA	Halogen Free
Cd	<100 ppm	N/A	N/A
Cr	Cr^{6+} <1000 ppm	N/A	N/A
Hg	<1000 ppm	N/A	N/A
Pb	<1000 ppm	<100 ppm substrate <90 ppm surface	N/A
Br	PBB PBDE <1000 ppm	N/A	<900 ppm
Cl	N/A	N/A	<900 ppm
Br + Cl	N/A	N/A	<1500 ppm

Figure 29. Portable Delta XRF device. Source: Olympus

DENSITY SEPARATION OF BFR PLASTICS THROUGH SINK/ FLOTATION.

An excellent analysis of the use of the sink float method of separation using polymer density is described in an analysis of chemical additives as barriers to recycling of plastics in the informal sector in India (Haarman and Gasser 2016). The study confirms that the sink/float method of separation for pre-shredded plastics has a high degree of effectiveness, and is the only method that has minimal occupational health concerns. Other methods, such as the Beilstein test which involves applying hot copper wire to plastic fragments to see if the flame glows green (halogen positive), can generate potentially harmful emissions and are not considered environmentally sound for this reason.

Haarman and Gasser investigated methods already employed by the informal sector in India to separate different polymer groups. They found freshwater can be used to separate polyolefins (PE, PP) from other plastics, and that water/ethanol mixtures can separate plastics with densities lower than freshwater (e.g. PE from PP). For brominate flame retarded plastics, salt solutions (e.g. with NaCl) can be used to separate polymers that have much higher densities (e.g. ABS/HIPS/PP20 from heavier plastics). They also describe how sink/float baths of different densities can be arranged in series to obtain several homogenous fractions.

They report that when a bath solution with a density of 1.08-1.10 g / cm^3 is used, the floating fraction of plastics will be free of plastics where BFRs have been intentionally added during manufacture. It may not segregate plastics that have been contaminated with trace levels of BFRs as a result of the use of contaminated recycled plastic in their production. Those plastics that sink are virtually all contaminated with BFRs as an intentional production additive. Some other heavier plastics can also end up in the polymers that sink including PVC, PC, and PET due to overlap in the density of the polymers, but carefully establishing different solution densities in subsequent baths can then separate these plastics into homogenous polymer groups.

The investigation of Indian informal sector techniques by Haarman and Gasser are largely supported by laboratory studies (Schlummer and Maurer, 2006, Lloyd-Smith and Immig 2018) on flotation density separation of brominated fractions of European WEEE plastics. Sink/float density separation techniques are not 100% effective but do have high rates of recovery and separation that may be applicable in countries with large informal sectors, limited resources for relatively expensive optical separator systems, and large stockpiles of plastic waste that must be sorted. The range of optical and frequency sorting technologies and vendors are not limited to those discussed above, which are presented as examples of different approaches that are available.

POPs IN MARINE PLASTIC LITTER

One of the more unusual categories of POPs-contaminated plastic waste is marine plastic litter. Numerous studies (Bouhroum *et al.*, 2019, Van *et al.*, 2012, Mato *et al.*, 2001, Endo *et al.*, 2005, Takada *et al.*, 2006, Ogata *et al.*, 2009) have demonstrated the occurrence of adsorption of persistent organic pollutants onto marine plastic litter. The mechanism is via the inherent hydrophobic nature of POPs which wish to move from a marine or aquatic matrix toward one where oils, fats, and hydrocarbons are present. The petrochemical basis of most plastics means that they are particularly vulnerable to lipophilic POPs adsorption. The adsorption of POPs onto the surfaces of plastic at up to one million times the concentration

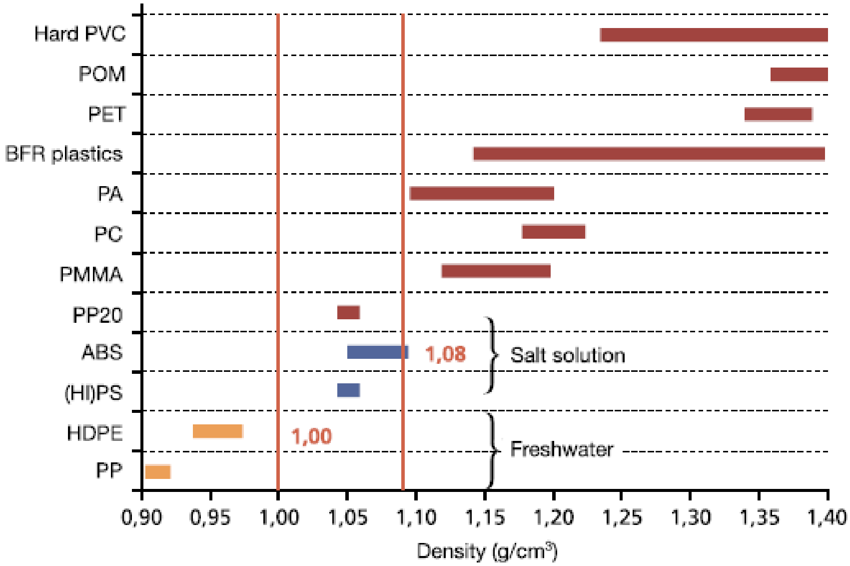


Figure 30. Density and solution application for different polymers.
Source: Haarman and Gasser 2016

in marine water has been identified as a significant new source of POPs-contamination of the food chain (Teuten *et al.*, 2009).

'Pellet Watch' is a unique scientific undertaking by Dr. Hideshige Takada at the Tokyo University of Agriculture and Technology. Dr. Takada and his team organize volunteers around the world to collect small plastic pellets from beaches according to a uniform protocol.

Dr. Takada explains, *"Plastic resin pellets are small granules generally with shape of a cylinder or a disk with a diameter of a few mm. These plastic particles are industrial raw material transported to manufacturing sites where "user plastics" are made by re-melting and moulding into the final products."* Because of dumping, spills, and the ubiquitous nature of plastic manufacture these pellets are now distributed in oceans across the globe.

These plastic pellets absorb persistent organic pollutants and other toxic chemicals such as PCBs, DDE, and nonylphenol. Sea creatures consume them mistaking them for food, and they move through the ocean washing up in estuaries and on beaches. When the volunteers return the pellets, they are analyzed at the Pellet Watch labs in Japan and the results are mapped on a global database showing relative levels of contaminants such as PCBs in different geographic areas (Figure 31). The results are

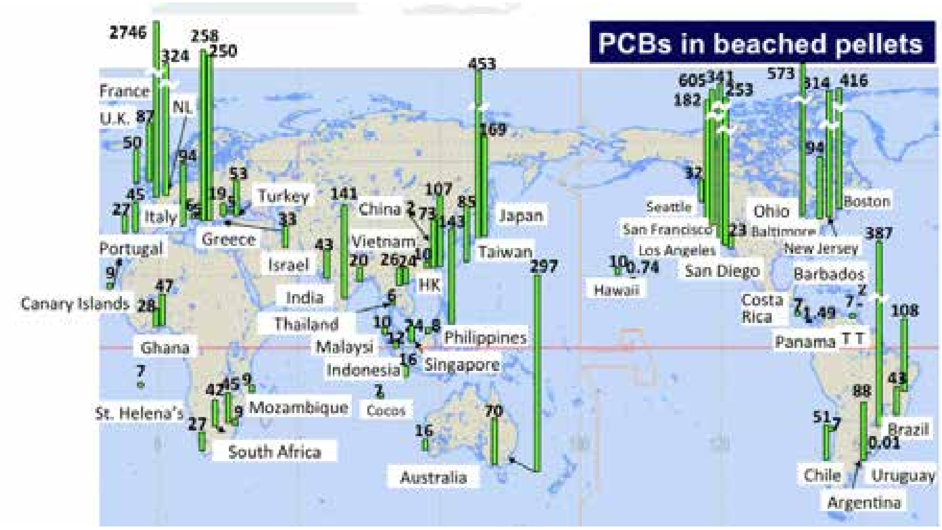


Figure 31. Pellet Watch mapping of PCB levels in globally dispersed plastic pellets. Numbers indicate ng/g-pellet.

then documented in peer-reviewed papers (Mato *et al.*, 2000, Endo *et al.*, 2005). The Pellet Watch[58] program is still underway, analyzing POPs-contamination of plastic from around the globe.

In addition to plastics that may enter the marine environment 'pre-loaded' with POPs additives such as brominated flame retardants, there is now a growing need to manage POPs-contaminated plastics that have adsorbed ambient POPs pollution in the marine environment onto their surfaces. Some well-meaning organizations have collected this type of marine litter only to burn it on beaches, promote crude pyrolysis conversion to fuels, or attempted other environmentally unsound management methods – often unaware of the contamination issues and the spread of POPs and UPOPs that these approaches involve. The technologies for environmentally sound management and destruction of POPs-contaminated waste described below are equally applicable to marine litter plastics impacts by POPs and plastics that have deliberate POPs additives.

---

[58] http://www.pelletwatch.org/en/what.html

6. NON-COMBUSTION TECHNOLOGIES FOR POPs-CONTAMINATED PLASTICS

The following technologies have the capability to either destroy POPs-contaminated plastic in an environmentally sound manner or separate the POPs from the plastic allowing the POPs to be destroyed and the plastic recycled.

GAS-PHASE CHEMICAL REDUCTION (HYDROGEN REDUCTION)

Gas-Phase Chemical Reduction (GPCR) was initially developed to destroy POPs waste such as PCBs. GPCR was developed in the 1980s in Canada, and operated at laboratory scale before being commercialized and operated at full commercial scale in the 1990s. A large-scale facility in Kwinana, Western Australia, operated for 5 years during the 1990s successfully, destroying that state's entire stockpile of PCBs and much of Australia's POPs stockpile. The same technology was developed further and later established at pilot and commercial scale in Canada, USA, and Japan, and has the demonstrated capability to destroy all POPs to high destruction efficiency (DE) levels.

GPCR technology is based on the use of hydrogen at elevated temperatures (approx. 875 °C) and low pressure to achieve thermochemical reduction of organic compounds. The contaminated bulk solids material is placed in a sealed chamber called a Thermal Reduction Batch Processor (TRPB), where the POPs are thermally desorbed and carried into the reactor by the heated hydrogen gas. Liquid POPs are preheated and injected directly into the TRBP. Bulk contaminated soils and sediments are processed in a TORBED Reactor System, a modified version of the TRPB allowing higher throughput.

Pre-treatment of some wastes is necessary, and the system requires electricity, hydrogen, water, and caustic for scrubbing. The 3rd generation of the technology (developed by Hallett Environmental & Technology Group Inc. of Ontario, Canada) can also generate energy from excess hydrogen-rich methane process gas that significantly exceeds the parasitic require-

Figure 32. GPCR unit running in Western Australia 1996. Source: Hallett Environmental & Technology Group Inc. 2018

Figure 33. Thermal Reduction Batch Processor (TRPB) of the GPCR unit. Source: Hallett Environmental & Technology Group Inc. 2018

ments of the process[59] and allows energy export. The reactions that occur generate methane and subsequently the methane is converted to hydrogen gas in a self-regenerating, recirculating process gas system.

The general chemistry of conversion of a hydrocarbon structure containing chlorine and possibly oxygen can be expressed in the following way:

$C_xH_yCl_xO_z + H_2 \rightarrow CH_4 + H_2O + HCl$ (thermal)

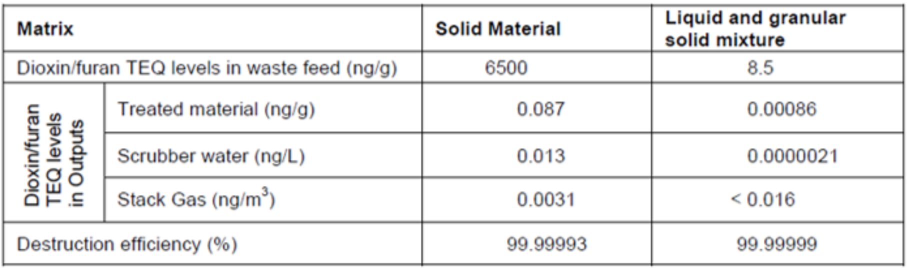
Methane is converted into hydrogen via the steam reforming and gas-water shift reactions, which are expressed as follows:

$CH_4 + H_2O \rightarrow H_2 + CO$ (steam reforming, catalytic)

$CO + H_2O \rightarrow CO_2 + H_2$ (water-gas shift, catalytic)

The process residues include scrubber liquor and water that is suitable for industrial discharge, and solid materials (metal drums, etc.) that are decontaminated and suitable for landfill. Emissions are primarily hydrogen chloride, methane, and other hydrocarbons, including benzene. An online mass spectrometer can analyze all reactor exit gases to ensure full dechlorination, and the gases, following scrubbing of the hydrogen chloride, can then be recirculated fully or split between the reactor and boiler fuel feed. The system can operate in modular, transportable and fixed modes, including transportable TRBPs to deal with on-site decontamination of POPs-contaminated sites.

A double TRBP system can process around 75 tons of solids per month. Liquid inputs can be processed at 2-4 liters per minute. A semi-mobile TORBED reactor can process around 300-600 tons per month. The main

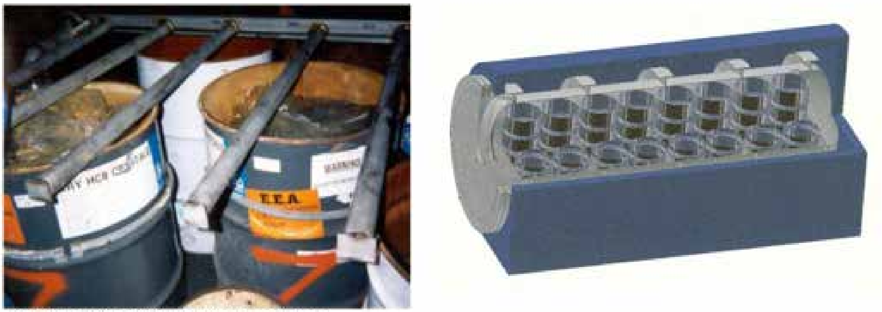


Matrix		Solid Material	Liquid and granular solid mixture
Dioxin/furan TEQ levels in waste feed (ng/g)		6500	8.5
Dioxin/furan TEQ levels in Outputs	Treated material (ng/g)	0.087	0.00086
	Scrubber water (ng/L)	0.013	0.0000021
	Stack Gas (ng/m^3)	0.0031	< 0.016
Destruction efficiency (%)		99.99993	99.99999

Figure 34. GPCR destruction efficiency for dioxins in waste. Source: Hallett Environmental & Technology Group Inc. 2018

---

[59] This refers to the energy required to run the technology.



Source: D Hallett True Energy Inc.

Figure 35. Bulk loading of plastic waste to the TRBP is possible.

advantages are complete destruction of all POPs, self-regeneration of hydrogen process gas, mobility and small footprint (1,000m2) for systems with a 70 ton/month throughput for smaller stockpiles or contaminated sites, low amounts of solid process residual and a long history of successful commercial utilization. Recent cost estimates for establishing a GPCR plant are around USD $50 million to construct and USD $1 million to train personnel.[60] This is around 10% of the cost of a modern waste incinerator. A new pilot-scale reactor is being developed in Canada to treat Automotive Shredder Residue (ASR), which is polymer material heavily contaminated with brominated flame retardants from car upholstery.

One of the advantages of this process to destroy POPs-contaminated plastics is that surplus hydrogen can be developed and used to process waste, as well as generate power. It also has few of the feedstock limitation of other technologies, allowing for loading of bulk materials into the TRBP.

BALL MILLING OR MECHANO-CHEMICAL DESTRUCTION (MCD)

This technology is a mechanochemical application that combines mechanical impact with chemical reagents to create a reduction reaction for chlorinated substrates such as PCB or pesticides. The objective is to achieve reductive dehalogenation of the POPs waste. The waste contaminated with POPs is placed into the ball mill device with an alkali metal compound that acts as a hydrogen donor, and is vibrated vigorously to permit agitation of the steel balls, reagent, and waste mix. The process is conducted at room temperature, in closed vessels, and no heating is re-

---

[60] pers comm Hallett Environmental & Technology Group Inc. 2018

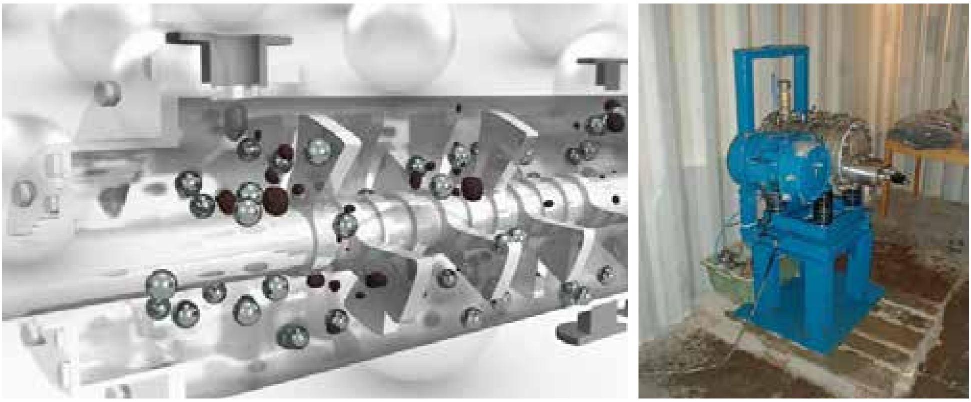


Figure 36. Illustration of the interior of a rotating ball mill. Source: EDL Asia

quired. There is no process gas to manage, avoiding the release of hazardous organic compounds.

Chlorine in the POPs waste is converted to inorganic compounds called $CaCl_2$ or Ca(ClOH). The reagents can include calcium oxide (CaO), magnesium (Mg), sodium, and other metals, including their oxides. The contaminated material is placed in the ball mill, which is essentially a metal vessel that can operate like batch reactor, or even as continuous reactors with the reagent and ball bearings. In addition to PCB and pesticides, it has also been successfully applied to dioxin-contaminated soils. Three commercial applications are well-developed and rely on the same principles: Tribochem's Dehalogenation by Mechanochemical Reaction (DMCR), EDL's Mechano-Chemical Destruction (MCD), and Radicalplanet (Research Institute Pty Ltd). Lab-based experiments using ball milling have also proven effective at destroying hexabromocyclododecane (Zhang *et al.*, 2014a) and polybrominated diphenyl ethers (Zhang *et al.*, 2014b).

One technology vendor (EDL Europe) describes their Mechano-Chemical Destruction (MCD) process: "*…the ball-to-ball and ball-to-surface collision points are the major regions of fracture and chemical reaction initiation. The reactions induced at the fracture point include radical formation and electron transfer resulting in the destruction of chemical bonds. EDL exploits these chemical phenomena to destroy even the most persistent contaminants which pose a threat to human and environmental health.*"

EDL uses a version of this technology they have patented known as Mechano-Chemical Destruction (MCD) to remediate soils and pesticides. In their version of the technology, an additional central spinning shaft fitted with rotors is included with the main reactor vessel. As the shaft spins it agitates the ball bearings at high speed, leading to a much higher rate of ball-to-ball and ball-to-surface impacts. The chemistry is very complex and relies on radical transformations involving metal-organic radical species. Simplified versions of the reactions are shown below (UNIDO, 2007).

$$RCl + Mg + RCl \rightarrow R\text{-}R + MgCl_2$$

$$RCl + Na + [H] \rightarrow R\text{-}H + NaCl$$

$$2C_xH_yCl + CaO \rightarrow CaCl_2 + H_2O + C2xH_{2y-2}$$

More recently, EDL Europe conducted a joint UNDP/GEF-funded trial remediation of a former US air base in Bien Hoa, Vietnam, treating 150 tons of soil contaminated with dioxin and dioxin-like PCB. The technology achieved high destruction efficiency for the dioxin, reducing its levels in soil down to as low as 1,000 ppt (1 ppb). A number of other technologies were trialled at the Bien Hoa site to assess suitability for the full-scale remediation of the site. MCD has been shortlisted in the selection criteria and cost estimates by comparison with incineration for the dioxin waste were around US $60 million less expensive for the MCD process, which does not generate UPOPs. They have also completed projects treating pesticides, PCB, and dioxins for the US military in Alaska and California, and for the Japanese government and multiple private projects. The first major site remediation was in Mapua, New Zealand, which was heavily contaminated with lindane, DDT, dieldrin, and aldrin. The site is now converted to mixed residential and recreational use.

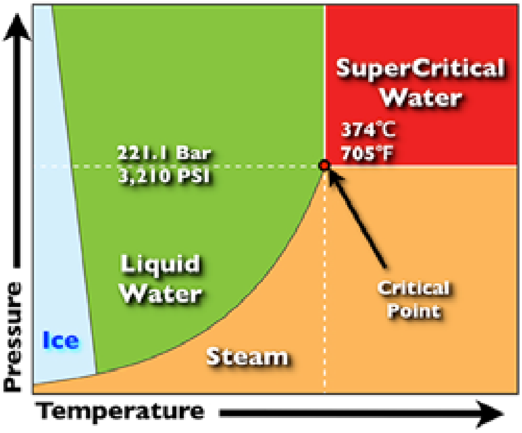
Ball milling has also been trialled favorably for its ability to debrominate plastics contaminated with brominated flame retardants which would allow the polymers to be recycled safely (Zhang *et al.,* 2014a and 2014b).

SUPERCRITICAL WATER OXIDATION (SCWO) AND INDUSTRIAL SUPERCRITICAL WATER OXIDATION (ISCWO)

Both supercritical and subcritical water oxidation systems have been developed by a number of companies over the last 30 years and some have substantial commercial experience in destroying POPs such as PCB. The technologies share similar principles of destruction of organics using an oxidant agent such as hydrogen peroxide, oxygen, or nitrite. The term 'supercritical' refers to the state of water just prior to its phase change from liquid to gas under heat and pressure (e.g. 374 °C and 218 atmospheres). Subcritical water refers to the state of water just below its critical level (e.g. 370 °C and 262 atmospheres). In this state, organic materials can be rapidly oxidized and decomposed. For destruction of PCB typical reaction conditions are a temperature of 400 - 500 °C, pressure 25MPa with a reaction time of 1 - 5 minutes.

Supercritical systems are generally injected with the waste along with water and oxygen into a column—mixed, heated and compressed to the point of supercriticality. The system is totally enclosed. The properties of the water in this phase have elevated molecular kinematic energy that is highly reactive, and combined with oxygen, can oxidize and destroy organic waste. The outputs of the reaction are nitrogen, water, and carbon dioxide. The destruction of chlorinated POPs results in an output of elevated hydrochloric acid. The highly acidic environment this generates requires the structural equipment of the process vessels to be corrosion-resistant, such as titanium alloys in combination with anti-corrosive additives, such as sodium carbonate. The process is not suited to bulk solids, but can treat

Figure 37. Parameters for Supercritical water.



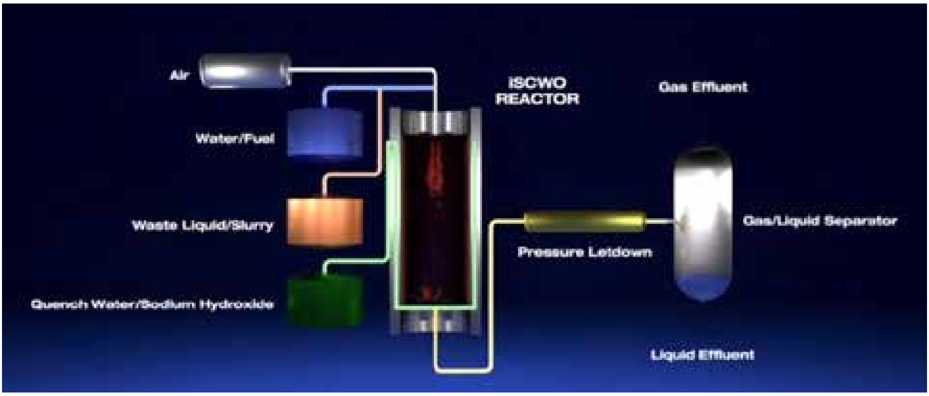
aqueous wastes, oils, solvents, slurries, and solids with a diameter less than 200 μm. Early versions of the technology were prone to corrosion but his has been resolved with the use of corrosion-resistant materials.

As of 2013, there were 3 fully operational plants, 5 constructed, and 9 planned for construction. In the interim, many of these plants will have become operational. The longest established plant is operated in Japan by Japan Environmental Safety Corporation (JESCO) for PCB destruction, with a capacity of 2,000 kg of PCB per day (Marrone *et al.,* 2013). While costs can vary significantly due to the capacity and type of SCWO developed, a study by Aki *et al.* (1998) found that destruction of hazardous waste from the petrochemical industry could be achieved at significantly lower costs by implementing SCWO rather than by using incineration. Installation costs were 15% less expensive and running costs for SCWO were only around 10% of the costs of incineration of hazardous liquids. SCWO is now used extensively by the US military for destruction of hazardous wastes and chemical weapons, including mobile ship-based units.

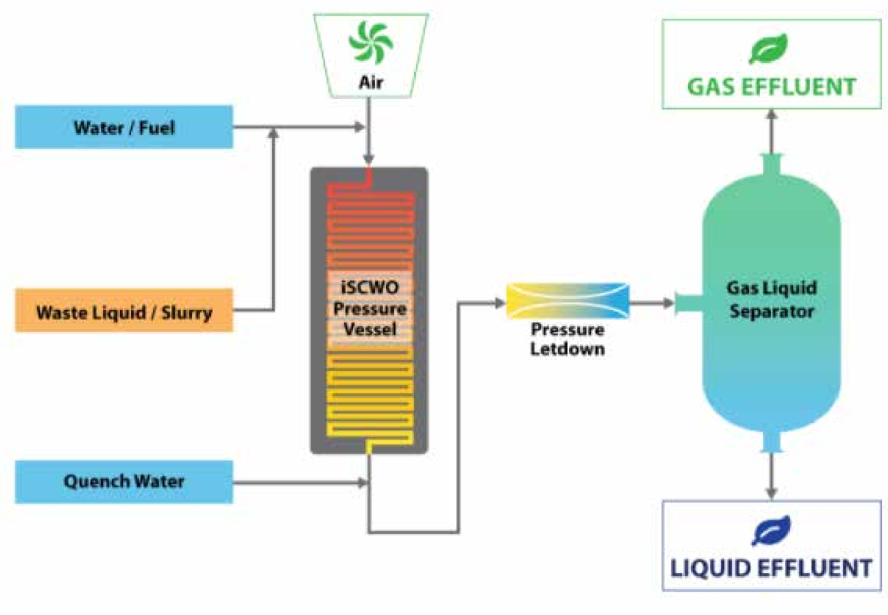
Marrone, in summarizing a comprehensive review of the global state of SCWO, notes that "*SCWO technology commercialization remains an area of great interest and activity.*" The main advantages of SCWO are very low emissions, low costs, high destruction efficiency, and low associated resources (catalysts) for operation in remote locations. Studies have been conducted on plastic waste SCWO by researchers (Goto 2016, Liu *et al.,* 2016) and industrial operators.

One company has developed the application to a higher degree of commercialization and can treat plastic waste. General Atomics has developed a relatively high throughput feed model designed for general industrial hazardous wastes, as well as non-hazardous waste. Their technology is referred to as Industrial Supercritical Water Oxidation or iSCWO. A GEF-funded project to treat large stockpiles of DDT waste in Kyrgyzstan is currently being implemented using the technology. While no stand-alone POPs plastics destruction facilities have been developed yet, the technology is capable of processing plastics. In addition, a number of SCWO plants have been operating to depolymerize plastics in Japan for two decades.

The General Atomics iSCWO operates with the following process: Air is pumped into the reactor vessel and pressurized to 3,200 psi and then heated to 650 °C. Water is pumped in and as the liquid flows into the reactor vessel pre-ignition is activated. Water is heated and pressurized above the thermodynamic critical point of 650 °C and 235 bar. When the stable critical point is reached, organic waste is mixed with quench water (and if required, sodium hydroxide). The supercritical conditions render organic materials, oxidation reactants, and oxidation products miscible in water and they are oxidised and destroyed. The remaining liquid is then discharged through a pressure let-down to atmospheric conditions.



The liquid and gas waste products from the process consist of carbon dioxide, water, and depending on the waste feed, salts and metallic oxides. Steam is vented to the atmosphere. There are no particulates released or pollution abatement filters required. Clean water is produced requiring no pre-treatment to dispose to sewer (elevated salinity and metal oxides limit the use of the effluent water).



THE CREASOLV® PROCESS

The CreaSolv® process was initially developed to maximize recycling opportunities for extruded polystyrene (XPS) waste that had been treated with brominated flame retardants listed as POPs under the Stockholm Convention, including PBDE and HBCD. Although the process is listed here as a method to treat POPs-contaminated plastics (by separating the POPs from the recyclate), it also meets the definition of 'chemical recycling' described elsewhere in this report. The CreaSolv® process does not destroy POPs, but acts as an effective separator, allowing the POPs to be concentrated and destroyed in one of the other technologies mentioned above or in other forms of non-combustion destruction technology.

The process uses a proprietary solvent to dissolve the plastic waste, and separate the contaminants and additives from target polymers. The polymers have a specific solubility, and the solvent can be targeted so as to select the target polymer and remove it at a high purity.

Following the dissolving phase, the solid material that remains is removed by mechanical means. Non-target polymers, additives, and hazardous substances, such as BFRs, are removed at molecular level using a purification process. At the post-purification stage, there remains a solution of macromolecules of target polymer, which is of virgin quality. The target polymer is then removed from the solvent by precipitation and dried. Any solvent recovered during the purification, drying, and precipitation stage is returned to the process. The target polymer can be used as feedstock in plastic production. In the case of extracting the BFRs, a second stage can be incorporated to recover the bromine, that incorporates incineration of the impurities and contaminants removed during the CreaSolv® process. Bromine is captured in selective scrubbers, and then on-sold to bromine product manufacturers. This secondary process is not necessary for the recovery of the plastic polymers and has significant environmental impacts due to the incineration step.

CreaSolv® was initially developed to treat, separate, and recycle polystyrene, and is successful and efficient at that task. However, more recently Unilever has attempted to use the technology to recycle polyethylene from small plastic packaging waste known as sachets. The sachets are used to package very small amounts of product including anything from shampoo to chilli sauce and are intended for purchase by people on extremely low incomes who cannot purchase larger volumes. The sachets are small, laminated, unrecyclable, and therefore have no value. As a result, they are a very visible aspect of plastic waste pollution in many developing countries. Unilever claims it can recycle the polyethylene, which accounts for 60% of the materials in the sachets.

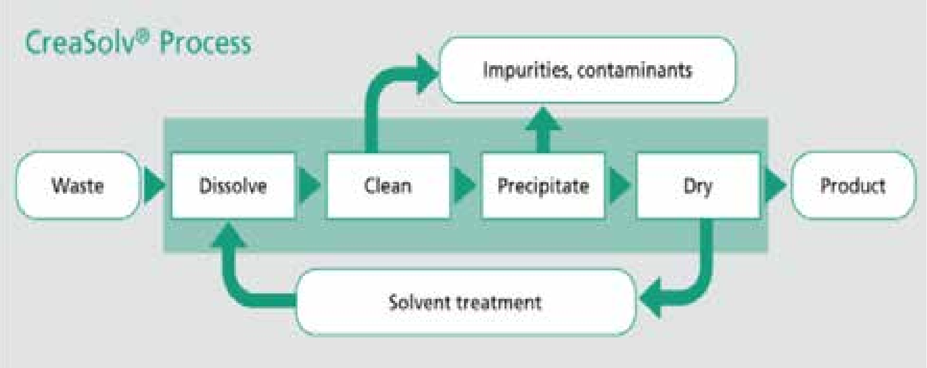


Figure 38. CreaSolv® process flow chart.

The official Unilever reports on their first, 3 ton per day, CreaSolv® Sachet recycling facility in Indonesia suggest it is working, but they are 'ironing out commercial and technical issues'[61] before upscaling to a 30 ton per day plant. There are still significant issues with the collection of the small plastic waste sachets, which have not been traditionally targeted by the informal recycling sector due to lack of value. NGOs monitoring the current operation have reported a number of fires at the plant and a shortage of sachets to process, as well as concerns that the process is being pushed to treat waste it was not intended for use with. More information is also required on the characterization, toxicity, and fate of the 40% of material not recovered in the sachet recycling process.

NON-COMBUSTION TECHNOLOGIES FOR MEDICAL PLASTIC WASTE

Under normal circumstances medical facilities generate significant quantities of medical waste, including infectious medical waste that must be carefully managed to ensure its disposal does not lead to unnecessary human exposure and spread of disease. A significant fraction of this waste is plastic and can include personal protective equipment (PPE), such as face masks and shields, hoods, gloves, aprons, and over-boots. It can also be found in the form of medical equipment, such as syringes, blood bags, tubing, bags, and so on. In unusual circumstances such as pandemics, the rate of accumulation of used medical waste plastic can accelerate rapidly, and management options will require capacity to treat such waste that may require transportable disinfection units.

---

[61] https://www.unilever.com/news/news-and-features/Feature-article/2018/our-solution-for-recycling-plastic-sachets-takes-another-step-forward.html

In the past medical waste incinerators were often used to dispose of infectious plastic medical waste. However, the high proportion of PVC used in medical PPE and other equipment leads to elevated dioxin emissions and contaminated ash from many incinerators, particularly in low-income countries, where waste incinerators are of rudimentary construction with little or no air pollution controls. The chlorine content of PVC has a significant influence on dioxin generation in combustion chambers.

Fortunately, there are commercially available and well-established non-combustion technologies to treat this form of waste. Most are different forms and sizes of autoclave disinfection units using steam treatment to disinfect medical waste. These range from quite small units for community clinics to large-scale industrial units for hospitals and medical waste treatment contractors. Some operate in fixed form and others are mobile. The autoclaves are relatively easy to operate compared to waste incinerators, and do not require the prohibitively expensive air pollution control (APC) equipment of medical waste incinerators. At a minimum, medical waste incinerators must be fitted with APC including electrostatic precipitators for particulates, activated carbon injection for dioxin and UPOPs minimization, and lime injection to reduce acid gas emissions. Some may also be equipped with baghouses which are expensive to install and maintain. Incinerators also generate significant greenhouse gases when compared to steam and microwave based non-combustion technologies.

Both the United Nations Environment Programme (UNEP) and the World Health Organization (WHO) support the use on non-combustion technologies ahead of incineration due to the UPOPs released from incineration technology (UNEP 2003, UNEP 2012). Combustion technologies other than incineration, such as cement kilns, are sometimes proposed for burning medical waste. However, cement kilns are not suitable for burning medical waste according to the Stockholm BAT BEP Guidance Part II Source category (b): Cement kilns firing hazardous waste.

Figure 39. L-R: Bondtech autoclave, on-site autoclaev with lift table at a hospital, waste dumper.

Figure 40a. Sanitech medical waste disinfection system as truck mounted and stationary units.

Figure 40b. Disinfected, shredded waste output from a Sanitech unit.

There are a large range of steam and microwave units available to suit most clinical applications and bulk treatment. A detailed assessment including throughput rates and residues are available in the 2012 UNEP Compendium of Technologies for Treatment /Destruction of Healthcare Waste.[62]

---

[62] Available online at http://wedocs.unep.org/handle/20.500.11822/8628

Autoclave units use steam instead of combustion for disinfection and do not require APC as they have no hazardous emissions. They do not produce a hazardous ash residue after treatment, rather they produce a disinfected version of the waste they treat. Most autoclave units are fixed, but there are some designs that are highly mobile such as Sanitech units. In Sanitech units, the waste is shredded and subject to steam disinfection via microwave heating. The Sanitech company suggests that the resulting waste stream is capable of being recycled as lower grade plastic products. This would depend to some degree on the feed input and separation of other materials, such as sharps and bandages, that would contaminate a potential recycling stream. The priority of autoclave technologies is disinfection and not recycling, so most outputs of the process are landfilled.

Sanitech units are operated with a top feed shredder that exposes the waste material to a high temperature, microwave heated steam environment via a worm screw to ensure residence time is sufficient to destroy any pathogens in the waste. A periodic test is conducted using *Bacillus atrophaeus* spores to validate microbial inactivation by inserting a capsule in waste batches, which is retrieved at the end of the process and analyzed to ensure full destruction of pathogens has taken place. It has a relatively high throughput at 810 kg/hr and operates in stationary configurations, which can be accommodated on hospital grounds, and in transportable mode (they are built within shipping container specifications). They also have purpose-converted trucks that house Sanitech units for rapid despatch to multiple facilities for batch treatment.

In pandemic situations, multiple units can be rapidly installed to treat higher than usual waste volumes or can be driven or shipped to more remote locations where outbreaks have occurred helping to minimize the transport of infectious waste and potential exposures. The Sanitec company claims that the residues from process can be recycled in lower grade plastic products but are commonly sent to municipal landfill.

7. INCINERATION OF PLASTIC WASTE

The use of incineration to generate energy (waste to energy) from plastic waste is widely acknowledged as counterproductive to a circular economy concept and mitigating climate change, at the same time as it generates toxic pollutants. The EU has an overcapacity of incineration developed as landfilling of waste was banned or subject to high disposal fees meant to deter dumping of wastes that could otherwise be recycled, as well as to protect groundwater supplies.

However, in recent years it was recognized that incineration of municipal waste, a large part of which is plastic, was consuming resources in a way inconsistent with the circular economy, in competion with recycling, and in some cases, resulting in waste having to be imported to feed the incinerators. In 2016, it was estimated that 11.3 million tons of plastic were incinerated in the EU – a 61% increase in a decade (Delva *et al.*, 2019).

> THE USE OF SEMI-CONTINUOUS SAMPLING EQUIPMENT HAS REVEALED 'HIDDEN DIOXIN EMISSIONS' THAT ARE NOT PICKED UP UNDER THE STANDARD METHODS USED FOR DECADES, AND COMMONLY STILL IN USE.

These concerns have led to EU proposals for taxes on waste incineration, and specifically plastic incineration. As of June 2018, The EU's budget commissioner, Günther Oettinger, has announced plans to introduce a new EU-wide tax of 80 Euro cents per every kilogram of plastic waste burned (€800 per metric tonne). Denmark has already imposed a tax on mixed waste incineration of USD $45 per ton (1016 kg).

In further recognition of the Global Warming Potential of incinerator emissions, the EU has excluded waste to energy and waste incineration from the newly developed Sustainable Finance Taxonomy.[63] The EU Commission has agreed that the taxonomy, a regulatory instrument to direct investment to climate change mitigation, should exclude incin-

---

[63] https://data.consilium.europa.eu/doc/document/ST-14970-2019-ADD-1/en/pdf

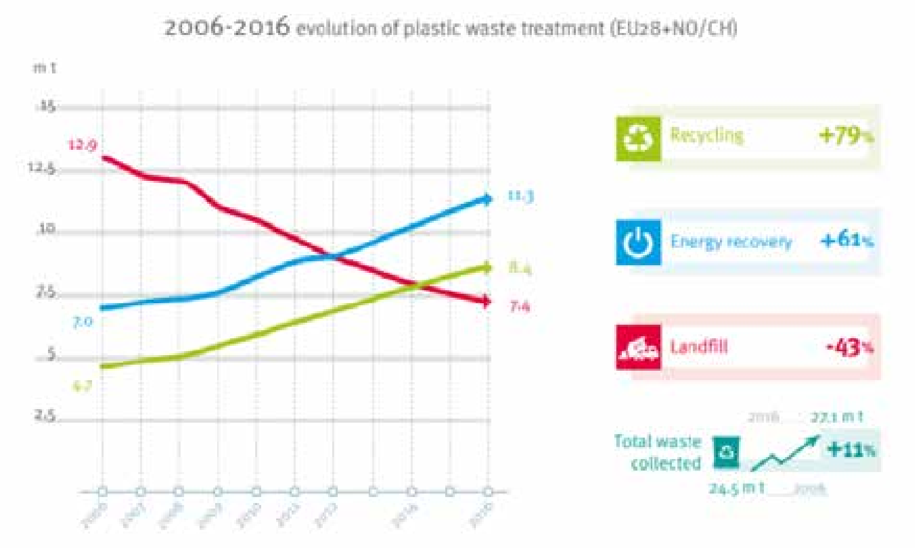
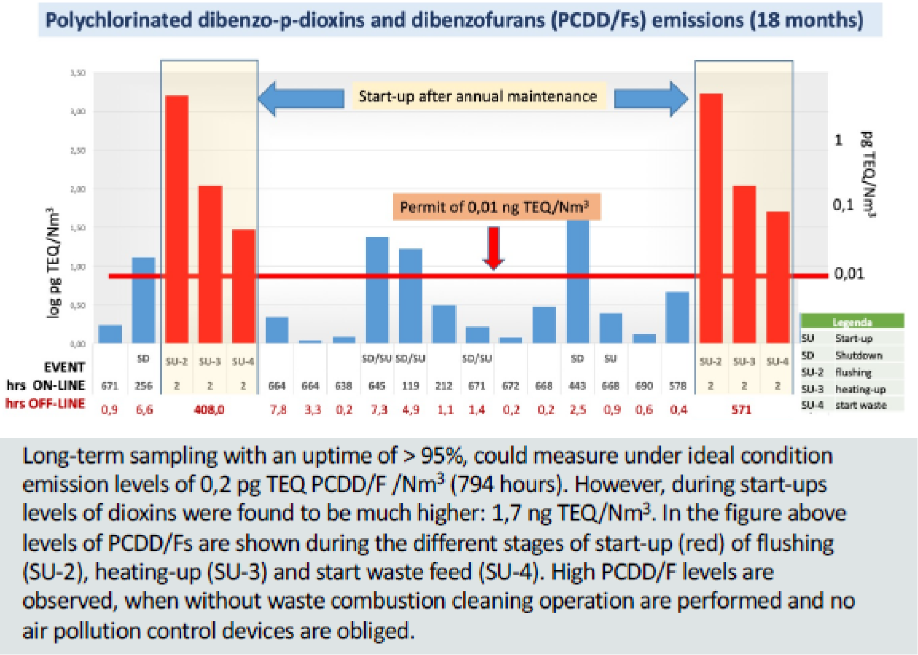


Figure 41. 2006-2016 plastic waste treatment evolution in Europe. Source: Delva et al. 2019

eration from its list of activities, with Article 9 stating that minimizing incineration and avoiding disposal of waste will contribute to the circular economy.

Aside from high volumes of climate damaging emissions, incineration of plastic waste also produces toxic compounds as emissions and residues. Emissions of highly toxic chemicals, such as persistent organic pollutants, in particular dioxins, have blighted the industry for decades with evidence of harm to human health from emissions and impacts on the food chain (Xu *et al.*, 2019, Tait *et al.*, 2019).

At enormous expense, modern incinerators have reduced atmospheric dioxin emissions significantly by transferring them, via filtration and scrubbing devices, to the solid residues of incineration – bottom ash and fly ash. However, this had led to evidence of food chain contamination, as the ash re-enters the environment (IPEN, Arnika, NTN 2017). In addition, questions are now being raised as to the real level of dioxin emissions from incinerators, as the regular monitoring technology and requirements have come under scrutiny. Standard equipment takes one or two 'snapshot' samples a year where new sampling units can generate almost continuous data. The use of semi-continuous sampling equipment has revealed 'hidden dioxin emissions' that are not picked up under the standard methods used for decades, and commonly still in use (Arkenbout and Petrlik 2019).



Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) emissions (18 months)

Long-term sampling with an uptime of > 95%, could measure under ideal condition emission levels of 0,2 pg TEQ PCDD/F /Nm^3 (794 hours). However, during start-ups levels of dioxins were found to be much higher: 1,7 ng TEQ/Nm^3. In the figure above levels of PCDD/Fs are shown during the different stages of start-up (red) of flushing (SU-2), heating-up (SU-3) and start waste feed (SU-4). High PCDD/F levels are observed, when without waste combustion cleaning operation are performed and no air pollution control devices are obliged.

Figure 42. Hidden dioxin emissions from a state-of-the-art incinerator, the Netherlands. Source: Arkenbout and Petrlik 2019

Long-term semi-continuous sampling by the AMESA system demonstrated that even a state-of-the-art incinerator in the Netherlands was emitting much higher levels of dioxin than were shown by the old standard monitoring method. Very high dioxin emissions were recorded during start-up conditions following internal cleaning maintenance of the incinerator (see Figure 42) using the AMESA system.

Additives in plastic can also lead to uncontrolled and unregulated emissions. As an example, the use of nanofillers in plastics can lead to chemicals of concern being emitted from the stacks of incinerators. Nanoparticle emissions from incinerators are entirely unregulated. According to the European Commission "*thermoplastics with nanofillers will generate significant levels of high-weight polyaromatic hydrocarbons (PAHs), which are considered more toxic than low-weight PAHs. These substances are assumed to be formed on the released nanoparticulate matter during thermal decomposition*" (European Commission, 2018).

In addition to toxic emissions, releases, and high GWP, incineration competes with recycling technology for materials such as plastics. In the past, the incinerator industry claimed that they must be a 'part of the mix' for the circular economy, and that their target waste is residual, post-recycling waste unmanageable by any other way than landfilling. However, the emergence of chemical recycling that can manage contaminated residual plastic waste may provide a better resource recovery outcome than incineration, which somewhat undermines the claim that incineration is the only option for such waste.

Incineration remains one of the most polluting 'false solutions' to the plastic pollution problem, and in the long-term, does not appear to have any role to play in the environmentally sound management of plastic waste in a circular economy.

8. LANDFILL

Landfill, like incineration for disposal, languishes at the bottom of the waste hierarchy due to its environmental impacts, especially on groundwater. The primary reason for the impacts of landfill containing municipal solid waste is the organic fraction of waste rotting and generating gases and a reducing environment within the landfill. The primary gas emission is methane from decomposing organic matter, a potent climate change pollutant. There are also dozens of secondary toxic gas emissions related to the breakdown of waste chemicals and products within the landfill. The leachate (liquids) in a reducing, anaerobic landfill environment tends to be acidic, and accelerate the leaching of toxic metals from waste materials. When the landfill liner eventually leaks, contaminated leachate enters and pollutes the groundwater beneath the landfill.

Landfills are usually only fully capped at the end of their space capacity, and then methane extraction systems can be employed to draw off methane and convert to energy or simply flare it. Some landfills can install methane extractors earlier in a staged manner to try and capture methane earlier in the life of the landfill. The expected methane generating life of a landfill is up to 50 years from decommissioning. There are not many reasons to recommend sanitary MSW landfills from an environmental perspective.

However, when comparing mono landfilling of plastic under controlled conditions, many of the problems of MSW landfill do not apply. If only plastic is interred in the absence of organic matter within a specifically designed dry landfill dedicated to plastic, the problems of methane generation and leachate are greatly reduced. While plastic can generate methane and ethylene (Royer *et al.*, 2018), it is mostly when subject to ambient solar radiation. When buried, this is greatly diminished.

Rain can also penetrate such a landfill unless is it capped and shielded in such a way to prevent precipitation entering the landfill and leaching toxic chemicals from the plastics.

WHY WOULD YOU LANDFILL PLASTIC WASTE?

Under normal circumstances and in mixed waste landfills, you would take all steps to avoid it. However, in certain circumstances it may be more environmentally sound to ‘store’ plastic waste in compressed bales underground (sorted by polymer preferably), as a transitional measure. The same may be argued for storing plastic above ground, but the potential for fires and the loss of valuable surface land may preclude this option. Dedicated, dry storage of plastic in landfill separate from any organic or other forms of waste may be necessary while the techniques for safe recycling of the plastics mature and become economically viable. ‘Banking’ plastic waste and its intrinsic value could assist remote communities, low-income countries, and isolated island nations to manage plastic waste without burning it, leaking it in an uncontrolled manner to the environment, or suffering exposure to the impacts of incineration.

Dedicated landfill storage of plastic wastes may be necessary in certain circumstances to allow technologies and regulation to ‘catch up’ with the waste problem, and permit decentralized, environmentally sound processing techniques to be established. At such a point the plastic waste can be unearthed and processed according to ESM, or exported to wealthy countries that have the processing capability.

In no way can this be considered a ‘solution’ to the plastic pollution issue - it is more a strategy borne out of necessity. The only long-term solution is to minimize the production of plastic.

REFERENCES

Adschiri, T., Lee, Y.-W., Goto, M., Takami, S., (2011) *Green Chem., 13,* 1380.

Alaerts, L., Augustinus, M., Van Acker, K. (2018) Impact of Bio-Based Plastics on Current Recycling of Plastics. *Sustainability,* 10, 1487; doi:10.3390/su10051487

Allen, S., Allen, D., Phoenix, V.R. *et al.* (2019) Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nat. Geosci. 12, 339–344* (2019). https://doi.org/10.1038/s41561-019-0335-5

American Chemical Society. (2008, June 7). Lead Leaching and Faucet Corrosion In PVC Home Plumbing. *ScienceDaily*. Retrieved May 25, 2020 from www.sciencedaily.com/releases/2008/06/080602091241.htm

Arkenbout A, and Petrlik, J. (2019) Hidden Emissions of UPOPs: Case Study of a

Waste Incinerator in The Netherlands. *Proceed. Dioxin 2019* Krakow Poland.

Andrady, A.L. (2011) Microplastics in the marine environment, *Mar. Pollut. Bull. 62*(2011) 1596–1605.

Bakir, A., Rowland, S., Thompson, R., (2014) Transport of persistent organic pollutants by microplastics in estuarine conditions, *Estuarine Coast. ShelfSci. 140* (2014) 14–21.

Bi, X., Simoneit, B., Wang, Z., Wang, X., Sheng, G., Fu, J. (2010) The major components of particles emitted during recycling of waste printed circuit boards in a typical e-waste workshop of South China, *Atmos. Environ. 44* (2010) 4440–4445.

Bignardi C, Cavazza A, Lagana C, *et al.* (2017). Release of non-intentionally added substances (NIAS) from food contact polycarbonate: Effect of ageing. *Food Control. 71*:329-35.

BLASTIC (2019) *Plastic waste pathways into the Baltic Sea.* https://www.blastic.eu/

Bouhroum, R., Boulkamh, A., Asia, L., Lebarillier, S., Ter Halle, A., Syakti, A., Doumenq, P., Malleret, l. and Wong-Wah-Chung, P., (2019) Concentrations and fingerprints of PAHs and PCBs adsorbed onto marine plastic debris from the Indonesian Cilacap coast and the North Atlantic gyre, *Regional Studies in Marine Science, Volume 29,* 2019, 100611, ISSN 2352-4855, https://doi.org/10.1016/j.rsma.2019.100611.

Bradley EL, and Coulier L. (2007). An investigation into the reaction and breakdown products from starting substances used to produce food contact plastics. *CSL York.*

Burat, F., Güney, A., and Kangal, A. (2009) Selective separation of virgin and post-consumer polymers (PET and PVC) by flotation method, *Waste Management, Volume 29, Issue 6,* 2009, Pages 1807-1813, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2008.12.018.

Cantwell, M. G. et al. Source determination of benzotriazoles in sediment cores from two urban estuaries on the Atlantic Coast of the United States. Mar. Pollut. Bull. 101, 208–218 (2015).

Centre for European Policy Studies (2017) The Circular Economy A review of definitions, processes and impacts. Research Report No 2017/08, April 2017

Chen, D., Yin, L., Wang, H. and He, P. (2014) Pyrolysis technologies for municipal solid waste: a review. *Waste Manag.* 34, 2466–2486

Centre for International Environmental Law (2019) Plastic & Climate: The Hidden Costs of a Plastic Planet. https://www.ciel.org/plasticandclimate/

Conesa, J., Font, R., Fullana, A., Martın-Gullon, I., Aracil, I., Galvez, A., Molto, J., Gomez-Rico, M. (2008) Comparison between emissions from the pyrolysis and combustion of different wastes. *J. Anal. Appl. Pyrol.*, doi:10.1016/j.jaap.2008.11.022

Creech Jr, J., and Johnson, M. (March 1974). "Angiosarcoma of liver in the manufacture of polyvinyl chloride". *Journal of Occupational Medicine. 16* (3): 150–1. PMID 4856325.

Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Linder, M., Muncke, J., ... Wagner, M. (2019). A circular economy for plastics: Insights from research and innovation to inform policy and funding decisions. *European Commission EC*. https://doi.org/10.2777/269031

Cruz, S and Zanin, M. (2006) PET recycling: Evaluation of the solid-state polymerization process March 2006 *Journal of Applied Polymer Science* 99(5):2117 - 2123
DOI: 10.1002/app.22526

ECHA. Estimating the number and types of applications for 11 substances added to the Authorisation List in February 2020. (2020) doi:10.2823/11134.

Endo, S., Takizawa, R., Okuda, K., Takada, H., Chiba, K., Kanehiro, H., Ogi, H., Yamashita, R., and Date, T. (2005) Concentration of polychlorinated biphenyls (PCBs) in beached resin pellets: variability among individual particles and regional differences. *Mar. Pollut. Bull. 50*, 1103–1114.

European commission (2018) *Incinerating nano-enabled thermoplastics linked to increased PAH emissions and toxicity*. Science for Environment Policy.

Espinosa, M., Blanco, A., Schmidgall, T., Atanasoff-Kardjalieff, A., Kappelmeyer, U., Tischler, D., Pieper, D., Heipieper, H. and Eberlein, C. (2020) Toward Biorecycling: Isolation of a Soil Bacterium That Grows on a Polyurethane Oligomer and Monomer. *Front. Microbiol.*, 27 March 2020 | https://doi.org/10.3389/fmicb.2020.00404

Fasano, E., Bono-Blay, F., Cirillo, T., Montuori, P., Lacorte, S. (2012) Migration of phthalates alkylphenols, bisphenol A and di(2-ethylhexyl)adipate from food packaging, *Food Control 27* (2012) 132–138.

Geyer, R., Jambeck, J. R. & Law, K. L. (2017). Plastics. Production, use and fate of all plastics ever made. *Science Advances* (3), 1-5.

Ghanta, M., Fahey, D. & Subramaniam, B. Environmental impacts of ethylene production from diverse feedstocks and energy sources. Appl Petrochem Res 4, 167–179 (2014). https://doi.org/10.1007/s13203-013-0029-7

Gleis, M., (2012). Gasification and pyrolysis - reliable options for waste treatment? In: Thomé-Kozmiensky, Thiel, S. (Eds.), *Waste Management 3*. Vivis, TK Verlag, pp. 403–410.

Goodson, A., Robin, H., Summerfield W., Cooper, I. (2004) Migration of bisphenol A from can coatings-effects of damage, storage conditions and heating, *FoodAddit. Contam. 21* (10) (2004) 1015–1026.

Goto, M. (2016). "Subcritical and Supercritical Fluid Technology for Recycling Waste Plastics." *Journal of the Japan Petroleum Institute 59*(6): 254-258.

Haberl, et. al., (2012) "Correcting a fundamental error in greenhouse gas accounting related to bioenergy," *Energy Policy, 45* (2012) 18–23, pp.19-20. http://www.sciencedirect.com/science/article/pii/S0301421512001681

Hahladakis, J., Velis, C., Weber, R., Iacovidou, E., and Purnell, P. (2018) An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *Journal of Hazardous Materials 344* (2018) 179–199.

Halden, R. (2010). Plastics and Health Risks. Annual Review of Public Health. 31: 179–94. doi:10.1146/annurev.publhealth.012809.103714

He, Z., Li, G., Chen, J., Huang, Y., An, T. and Zhang, C. (2015) Pollution characteristics and health risk assessment of volatile organic compounds emitted from different plastic solid waste recycling workshops, *Environ. Int. 77* (2015) 85–94.

Huang, D., Zhou, S., Hong, W., Feng, W. and Tao, L. (2013) Pollution characteristics of volatile organic compounds, polycyclic aromatic hydrocarbons and phthalate esters emitted from plastic wastes recycling granulation plants in Xingtan Town South China, *Atmos. Environ. 71* (2013) 327–334.

Ignatyev, I.A., Thielemans, W., Vander Beke, B., (2014) Recycling of Polymers: A Review. Chemsuschem 7, 1579-1593.

IPEN ARNIKA (2017a) *Toxic Toy or Toxic Waste: Recycling POPs into New Products. A Summary for decision makers*. International Pollutants Elimination Network and Arnika Association. Gothenburg and Prague. 2017. https://ipen.org/sites/default/files/documents/toxic_toy_report_2017_update_v1_5-en.pdf

IPEN, ARNIKA, NTN (2017b) *Toxic Ash Poisons the Food Chain.* International Pollutants Elimination Network, Arnika Association and National Toxics Network (Australia). Gothenburg, Prague and Perth. 2017. https://ipen.org/documents/toxic-ash-poisons-our-food-chain

IPEN, ARNIKA (2018) *Toxic Soup: Dioxin in Plastic Toys.* International Pollutants Elimination Network and Arnika Association. Gothenburg and Prague. 2018. https://ipen.org/documents/toxic-soup-dioxins-plastic-toys

International Pellet Watch (2020) Global survey of benzotriazole-type UV stabilizers in microplastics (pellets and fragments) unpublished data.

Katami, T., Yasuhara, A., Okuda, T., Shibamoto, T., *et al.* (2002). "Formation of PCDDs, PCDFs, and Coplanar PCBs from Polyvinyl Chloride during Combustion in an Incinerator".*Environ. Sci. Technol.* **36** (6): 1320–1324.

Kasier, K., Schmid, M. & Schlummer, M. (2018). Recycling of Polymer-Based Multilayer Packaging: A Review. *Recycling, 3, 1,* doi:10.3390/recycling3010001.

Kubwabo, C., Kosarac, I., Stewart, B., Gauthier, B., Lalonde, K. and Lalonde, P. (2009) Migration of bisphenol A from plastic baby bottles, baby bottle liners and reusable polycarbonate drinking bottles, Food Addi. Contamin.: Part A 26(2009) 928–937.

Labunska, I., Harrad, S., Santillo, D., Johnston, P. and Brigden, K. (2013) Levels and distribution of polybrominated diphenyl ethers in soil sediment and dust samples collected from various electronic waste recycling sites within Guiyu town, southern China, *Environ. Sci.: Processes Impacts 15* (2013) 503–

Lettieri, P. and Baeyens, J. (2009) "Recycling and recovery routes of plastic solid waste (PSW): A review," *Waste Manag., vol. 29, no. 10*, pp. 2625–2643, 2009.

Liu, K., *et al.* (2016). "Advanced degradation of brominated epoxy resin and simultaneous transformation of glass fiber from waste printed circuit boards by improved supercritical water oxidation processes." *Waste Manag 56*: 423-430.

Lloyd-Smith, M and Immig, J. (2018) Ocean Pollutants Guide: Toxic Threats to Human Health and Marine Life. *Prepared for the International Pollutants Elimination Network (IPEN) and the National Toxics Network (Australia).* October 2018. https://ipen.org/sites/default/files/ documents/ipen-ocean-pollutants-v2_1-en-web.pdf

Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C. and Kaminuma, T. (2001) Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. *Environ. Sci. Technol. 35,* 318–324.

McClarty, D., Brouwer, J., and Ainscough, C. (2015) Economic analysis of fuel cell installations at commercial buildings including regional pricing and complementary technologies. *Energy and Buildings 113* (2016) 112–122.

Mersiowski I. and J. Ejlertsson (1999). *"Long-term Behaviour of PVC Products Under Landfill Conditions."* Technical University of Hamburg-Harburg, Germany; Linköping University, Sweden, July.

Mukherjee, A., Debnath, B., and Sadhan Kumar Ghosh, A Review on Technologies of Removal of Dioxins and Furans from Incinerator Flue Gas, *Procedia Environmental Sciences, Volume 35,* 2016, Pages 528-540, ISSN 1878-0296, https://doi.org/10.1016/j.proenv.2016.07.037.

M.R.G. PlasticsEurope (MRG) (2008), *Business Data and Charts 2007.* Status September 2008. Plastics Europe Association of Plastics Manufacturers.

Nagase, Y., Yamagata, M., Matsuda, T., Naito, T., Kodama, K. and Fukuzato, R. (1998) *Proc. 5th Meeting on Supercritical Fluids.* P.127.

Nam, S., Seo, Y., Kim, M. (2010) Bisphenol A migration from polycarbonate baby bottle with repeated use, *Chemosphere 79* (2010) 949–952.

Nelms, S.E., Barnett, J., Brownlow, A. *et al.* (2019) Microplastics in marine mammals stranded around the British coast: ubiquitous but transitory? *Sci Rep 9, 1075* (2019). https://doi.org/10.1038/s41598-018-37428-3

Nkwachukwu, O.I., Chima, C.H., Ikenna, A.O. *et al.* (2013) Focus on potential environmental issues on plastic world towards a sustainable plastic recycling in developing countries. *Int J Ind Chem 4*, 34 (2013). https://doi.org/10.1186/2228-5547-4-34

Ogata, Y., Takada, H., Mizukawa, K., Hirai, H., Iwasa, S., Endo, S., (2009) International pellet watch: global monitoring or persistent organic pollutants (POPs) in coastal waters. 1. Initial phase data on PCBs, DDTs, and HCHs. *Mar. Pollut. Bull.* 58, 1437–1446.

Onwudili, J. A., Insura, N. and Williams, P. T. (2009). Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: Effects of temperature and residence time. *Journal of Analytical and Applied Pyrolysis, Volume 86, Issue 2*, 293-303.

Pascoe, R.D. (2006) Investigation of hydrocyclones for the separation of shredded fridge plastics, *Waste Management, Volume 26, Issue 10,* 2006, Pages 1126-1132, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2005.06.017.

Petrlik, J., Behnisch, P. and DiGangi, J. (2018) Toxic Soup: Dioxins in Plastic Toys. Arnika Association, Prague and IPEN, Gothenburg.

Pivnenko, K., Eriksen, M., Martín-Fernández, J., Eriksson, E., Astrup, T. (2016) Recycling of plastic waste: presence of phthalates in plastics from households and industry, *Waste Manage. 54* (2016) 44–52.

PlasticsEurope (2015) Plastics – the Facts 2015. An analysis of European plastics production, demand and waste data. https://www.plasticseurope.org/application/files/3715/1689/8308/2015plastics_the_facts_14122015.pdf

PlasticsEurope (2018) Plastics - The Facts 2018: An Analysis of European Plastics Production, Demand and Waste Data," 2018. https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf

PlasticsEurope (2019) Plastics - The Facts 2019: An Analysis of European Plastics Production, Demand and Waste Data," 2019 https://www.plasticseurope.org/application/files/9715/7129/9584/FINAL_web_version_Plastics_the_facts2019_14102019.pdf.

Puype, F., Samsonek, J., Knoop, J., Egelkraut-Holtus, M., Ortlieb, M. (2015) Evidence of waste electrical and electronic equipment (WEEE) relevant substances in polymeric food-contact articles sold on the European market, *Food Addit.Contam. Part A Chem. Anal. Control Exposure Risk Assess.* 32 (2015)410–426.

Ragaert, K., Delva, L. and Geem K. Van, (2017) "Mechanical and chemical recycling of solid plastic waste," *Waste Manag.,* 2017.

Ragaert, K. (2016) "Trends in mechanical recycling of thermoplastics," *in Conference: Kunststoff Kolloquium* Leoben, 2016.

Royer S-J, Ferrón S, Wilson ST, Karl DM (2018) Production of methane and ethylene from plastic in the environment. *PLOS ONE* 13(8): e0200574. https://doi.org/10.1371/journal.pone.0200574

Ryan (2015), A Brief History of Marine Litter Research, in M. Bergmann, L. Gutow, M. Klages (Eds), *Marine Anthropogenic Litter*, Berlin Springer, 2015, Plastics Europe.

Schlummer, M. and Mäurer, A. (2006) Recycling of styrene polymers from shredded screen housings containing brominated flame retardants. *Journal of Applied Polymer Science*, 15 October 2006, Vol.102(2), pp.1262-1273

Searchinger, T (2010) "Biofuels and the need for additional carbon," *Environmental Research Letters 5* (2010) 024007. http://iopscience.iop.org/1748- 9326/5/2/024007/pdf/1748-9326_5_2_024007.pdf

Takada, H., Mato, Y., Endo, A., Yamashita, R., Zakaria, M.P. (2006) Call for pellets! International pellet watch global monitoring of POPs using beached plastic resin pellets. *Mar. Pollut. Bull. 52,* 1547–1548.

Takada, H., Tanaka, K., Yamashita, R. & Watanuki, Y. ENVR 139: Transfer of additives from ingested plastics to seabirds and their accumulation in the tissue. in ACS Spring 2019 National Meeting & Exposition (2019).

Tanaka, K., Yamashita, R. & Takada, H. Transfer of Hazardous Chemicals from Ingested Plastics to Higher-Trophic-Level Organisms. in (eds. Takada, H. & Karapanagioti, H. K.) 267–280 (Springer International Publishing, 2019). doi:10.1007/698_2018_255.

Tanaka, K. et al. Accumulation of plastic-derived chemicals in tissues of seabirds ingesting marine plastics. Mar. Pollut. Bull. 69, 219–222 (2013).

Tanaka, K., van Franeker, J. A., Deguchi, T. & Takada, H. Piece-by-piece analysis of additives and manufacturing byproducts in plastics ingested by seabirds: Implication for risk of exposure to seabirds. Mar. Pollut. Bull. 145, 36–41 (2019).

Tanaka, K. et al. In Vivo Accumulation of Plastic-Derived Chemicals into Seabird Tissues. Curr. Biol. 30, (2020).

Tait, P., Brew, J., Che, A., Constanzo, A., Danyluk, A., Davis, M., Khalaf, A., McMahon, K., Watson, A., Rowcliff, K. and Bowles, D. (2019) The health impacts of waste incineration: a systematic review. *Aust NZ J Public Health*. 2019; Online; doi: 10.1111/1753-6405.12939

Tang, Z., Huang, Q., Cheng, J., Yang, Y., Yang, J., Guo, W., Nie, Z., Zeng, N. and Jin, L. (2014) Polybrominated diphenyl ethers in soils, sediments, and human hair in a plastic waste recycling area: a neglected heavily polluted area, *Environ. Sci.Technol. 48* (2014) 1508–1516.

Teuten, E.L., Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Bjorn, A., Rowland, S.J., Thompson, R.C., Galloway, T.S., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Viet, P.H., Tana, T.S., Prudente, M., Boonyatumanond, R., Zakaria, M.P., Akkhavong, K., Ogata, Y., Hirai, H., Iwasa, S., Mizukawa, K., Hagino, Y., Imamura, A., Saha, M. and Takada, H., (2009) Transport and release of chemicals from plastics to the environment and to wildlife. *Phil. Trans. R. Soc. B. 364,* 2027– 2045.

Tollefson, J (2013) Methane leaks erode green credentials of natural gas. *Nature* 493, 12 (03 January 2013)

Tournier, V., Topham, C.M., Gilles, A. *et al.* (2020) An engineered PET depolymerase to break down and recycle plastic bottles. Nature 580, 216–219 (2020). https://doi.org/10.1038/s41586-020-2149-4

Uekert, T., Kuehnel, M., Wakerley, D. and Reisner, E. (2018) Plastic waste as a feedstock for solar-driven H2 generation *Energy Environ. Sci., 2018*,11, 2853-2857.

UNEP (2003) *Technical Guidelines on the Environmentally Sound Management of Biomedical and Healthcare Wastes (Y1; Y3*). United Nations Environment Programme

UNEP (2012) *Compendium of Technologies for Treatment/Destruction of Healthcare Waste.* United Nations Environment Programme. http://wedocs.unep.org/handle/20.500.11822/8628

UNEP, (2016) *Marine Plastic Debris and Microplastics. Global Lessons and Research to Inspire Action and Guide Policy Change*, (2016) United Nations Environment Programme

UNEP/POPS/POPRC.16/4 (2020) Proposal to list UV-328 in Annex A to the Stockholm Convention on Persistent Organic Pollutants

Van, A., Rochman, C., Flores, E., Hill, K., Vargas, E., Vargas, S. and Hoh, E. (2012) Persistent organic pollutants in plastic marine debris found on beaches in San Diego, California, *Chemosphere, Volume 86*, *Issue 3*, 2012, Pages 258-263, ISSN 0045-6535, https://doi.org/10.1016/j.chemosphere.2011.09.039.

Watson, A., Brigden, K., Shinn, M. and Cobbing, M. (2010) Toxic Transformers; - a review of the hazards of brominated & chlorinated substances in electrical and electronic equipment. Greenpeace Research Laboratories Technical Note 01/2010.

Weber, R., Kuch, B. (2003) Relevance of BFRs and thermal conditions on the formation pathways of brominated and brominated–chlorinated dibenzodioxins and dibenzofurans, *Environ. Int. 29* (2003) 699–710.

Weatherby, G., Baldwin, A., and Ranville, J. (2019) It's raining plastic. *US Geological Survey. Open-File Report 2019–1048* https://pubs.usgs.gov/of/2019/1048/ofr20191048.pdf

Whitehead, T. P., Brown, F. R., Metayer, C., Park, J. S., Does, M., Petreas, M. X., Buffler, P. A., & Rappaport, S. M. (2013). Polybrominated diphenyl ethers in residential dust: sources of variability.*Environment international,57-58*, 11–24. https://doi.org/10.1016/j.envint.2013.03.003

Wowkonowicz P and Kijeńska M (2017) Phthalate release in leachate from municipal landfills of central Poland. *PLOS ONE* 12(3): e0174986. https://doi.org/10.1371/journal.pone.0174986

Xu, P., Wu, L., Chen, Y., Xu, D., Wang, X., Shen, H., Han, J., Fu, Q., Chen, Z., and Lou, X. (2019) High intake of persistent organic pollutants generated by a municipal waste incinerator by breastfed infants. *Environmental Pollution 250* (2019) 662e668

Zhang, K., Huang, J., Wang, H., Yu, G., Wang, B., Deng, S. and Liu, K. (2014a) Mechanochemical degradation of hexabromocyclododecane and approaches for the remediation of its contaminated soil. *Chemosphere. 2014* Dec;116 40-45. doi:10.1016/j.chemosphere.2014.02.006. PMID: 24613442.

Zhang, K., Huang, J., Wang, H., Yu, G., Wang, B., Deng, S., Kanoband, J., and Zhang, Q. (2014b) Mechanochemical destruction of decabromodiphenylether into visible light photocatalyst BiOBr. *RSC Advances 4(28):*14719-1472 DOI: 10.1039/c3ra47738j

Zion Market Research (2019) "Plastic Additives Market by Type (Plasticizers, Stabilizers, Flame Retardants, Impact Modifiers, and Others) and by Application (Packaging, Automotive, Consumer Goods, Construction, and Others): Global Industry Perspective, Comprehensive Analysis, and Forecast, 2018–2025"

ACKNOWLEDGMENTS

IPEN would like to acknowledge that this document was produced with financial contributions from the Government of Sweden, the Plastic Solutions Fund, and other donors. The views herein shall not necessarily be taken to reflect the official opinion of any of these donors.

International
Pellet Watch

http://pelletwatch.org/

IPEN
for a toxics-free future

www.ipen.org

ipen@ipen.org

@ToxicsFree