



# Safety first

Recovering value from plastic waste in low- and middle-income countries

A report prepared for Tearfund and funded by the Norwegian Agency for Development Cooperation (NORAD)

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# Acknowledgements

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- *Mismanagement of plastic waste through open burning with emphasis on the Global South: A systematic review of risks to occupational and public health* (Velis and Cook, 2021);
- *Breaking the plastic wave* (SYSTEMIQ and The Pew Charitable Trust, 2020);
- *Evaluating scenarios towards zero plastic pollution* (Lau et al., 2020);
- *Global review on safer end of engineered life* (Cook and Velis, 2020);
- *Plastic waste reprocessing for circular economy: A systematic review of risks to occupational and public health from legacy substances and extrusion* (Cook et al. 2020);
- *Eliminating avoidable plastic waste by 2042: A use-based approach to decision and policy making* (Resource Futures-Nextek, 2018);
- *Improving markets for recycled plastics: Trends, prospects and policy responses* (Lerpiniere and Cook, 2018).

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## Reviewers

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## Safety first: Recovering value from plastic waste in low- and middle-income countries

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# Foreword

This paper is intended to highlight and partially address a major gap in the landscape of literature and practice on waste plastics. Across the world, a variety of new methods for treating waste plastics have emerged in recent years, both at the macro and micro scales. However, relatively little has been done to assess and compare the safety of these approaches from a human and environmental standpoint.

This paper is not intended to signal that the plastics crisis can be solved through collection and recycling alone. Action to substantially reduce single-use plastic and replace it with refillable, reusable and packaging-free alternatives should be our first response. However, in a crisis of this magnitude we need to take action at every level simultaneously – safe collection and recycling is one way of doing so.

Tearfund's Rubbish Campaign drew attention to the scandal of mismanaged waste, and single-use plastic packaging in particular. It has led to us pursuing an increasing programme of research and advocacy aimed at improving decision-making around safer waste management. The statistics speak for themselves:

- As many as one million people die each year from diseases caused by plastic and other mismanaged waste. ([No time to waste](#), Tearfund, 2019)
- Two billion people, one in four of us globally, do not have access to regular bin collections. ([No time to waste](#), Tearfund, 2019)
- Each year, fast-moving consumer goods (FMCG) companies distribute billions of pieces of single-use plastic packaging in countries and contexts where large amounts will end up burned on street corners and open dumps, or dumped on land or in waterways. ([The burning question](#), Tearfund, 2019)

Tearfund is calling on large FMCG companies – and in particular, Coca-Cola, Nestlé, PepsiCo and Unilever – to do four things (in summary):

1. declare the amount of plastic they use in each country,
2. reduce this substantially,
3. collect and recycle what's left, and
4. do so through developing fair partnerships with waste pickers.

Change has begun to happen, albeit slowly and fitfully (see [Rubbish Campaign league table](#)).

As FMCG companies begin to reduce the amount of plastic packaging they place on the market, and in particular to collect more of what's left, clear questions are emerging. What should happen to plastic that has been collected for recycling? Where should recycling investments be directed? As NGOs and social enterprises have begun to address the scandal of plastic waste locally, similar issues have surfaced in relation to micro-level processing techniques. And policy-makers have found themselves facing dilemmas as mandatory Extended Producer Responsibility systems are designed.

This paper, summarising an independent academic review, is primarily intended to speak to FMCG companies, although we hope it will also prove useful for policy-makers, activists and community practitioners asking similar questions.

**Nigel Harris**  
Chief Executive, Tearfund

# Contents

<b>Executive summary</b>	1	<b>4.5 Approach 5: Chemical depolymerisation (chemolysis)</b>	19
<b>Glossary of terms and abbreviations</b>	4	4.5.1 Overview	19
<b>1 Introduction</b>	6	4.5.2 Environment	19
1.1 Scope	7	4.5.3 Health	19
<b>2 Method and structure of this review</b>	9	<b>4.6 Approach 6: Pyrolysis and gasification</b>	19
<b>3 What does it mean to recover value from plastic packaging waste safely?</b>	10	4.6.1 Overview	19
3.1 Prevalence and maturity	11	Pyrolysis	19
3.2 Environmental safety	11	Gasification	19
3.3 Occupational and public health	12	4.6.2 Environment	20
<b>4 Approaches to managing plastic packaging waste</b>	13	4.6.3 Health	21
4.1 <b>Approach 1: Conventional mechanical reprocessing for extrusion</b>	13	<b>4.7 Approach 7: Co-processing in cement kilns</b>	22
4.1.1 Overview	13	4.7.1 Overview	22
4.1.2 Environment	13	4.7.2 Environment	23
Global warming potential	13	4.7.3 Health	23
Water use	13	<b>4.8 Approach 8: Incineration with energy recovery</b>	23
Management of residues	14	4.8.1 Overview	23
4.1.3 Health	14	4.8.2 Environment	24
Occupational risk during plastic reprocessing	14	4.8.3 Health	25
Food contact applications and legacy substances	14	<b>5 Discussion</b>	26
<b>4.2 Approach 2: Bottle-to-fibre reprocessing</b>	15	5.1 Commercial maturity and data availability	26
4.2.1 Overview	15	5.2 Environmental impact	27
4.2.2 Environment	15	5.2.1 Carbon emissions	27
Global warming potential	15	5.2.2 Management of residues and pellet loss	27
Water use	15	5.3 Health	27
Management of residues	16	<b>6 Conclusion and recommendations</b>	28
Microplastic fibre release	16	Group 1a	28
4.2.3 Health	16	Group 1b	28
<b>4.3 Approach 3: Mineral-polymer composites</b>	16	Group 2	28
4.3.1 Overview	16	Group 3	29
Road surfacing	16	Assurance	29
Bricks and tiles	16	<b>7 References</b>	30
Dry aggregate in concrete	16	<b>Appendix: Detailed Approach</b>	42
4.3.2 Environment	17	A1 Scope, definitions and report structure	42
Road surfacing (Polymer-modified bitumen)	17	A2 Literature review	43
Brick and tile production	17	A3 Inclusion/exclusion criteria	43
4.3.3 Health	17	A4 Visual assessment of online media	44
<b>4.4 Approach 4: Solvent-based purification</b>	18		
4.4.1 Overview	18		
4.4.2 Environment	18		
4.4.3 Health	18		

# Executive summary

Alongside efforts to reduce plastic waste, large amounts of plastic waste will be collected for recycling over the next decade as a result of commitments made by some of the world's largest fast-moving consumer goods (FMCG) companies. Processing the additional material will require a massive upscale to infrastructure and changes to the logistical networks through which plastic waste flows from the point of generation to its transformation into useful products. Stakeholders across the plastic waste value chain are eager to explore new and innovative ways to process plastic waste to retain the maximum value from its material or energetic properties. New technologies under the banner of 'chemical recycling' (eg pyrolysis, depolymerisation and solvent-based purification) are being explored by innovators, who are keen to extol their potential to reduce material losses and energy use in comparison to more conventional approaches. In several examples, plastic waste that has been collected for recycling has been diverted to processes that seek to recover energy or convert it into fuel; particularly where the material is unsuitable for conventional mechanical reprocessing or where recycling infrastructure is lacking.

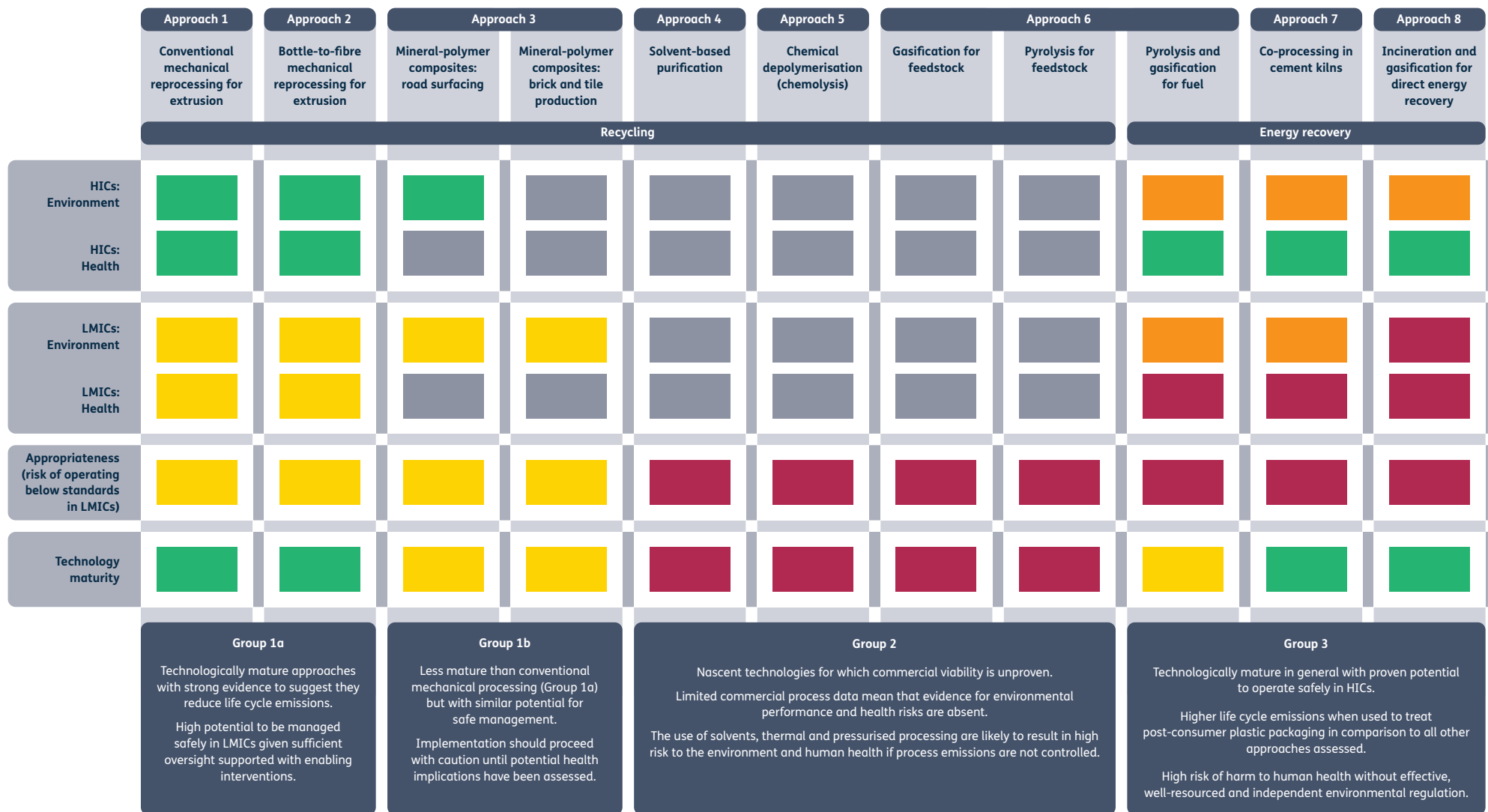
In this rapidly evolving landscape, people have started to question whether some of the processes used to recover value from plastic waste result in a better overall outcome for human health and the environment. A particular concern is that technology will be implemented in countries that lack effective, well-resourced and independent regulation, resulting in the emission of hazardous substances and materials into the environment. This review was written to improve understanding of some of these approaches, new and old, and to answer questions about which technologies should be supported. Eight approaches were identified for being actively explored by FMCG companies as potential solutions to the plastic pollution crisis ([Table 1](#)). Evidence for their impact on human health and the environment is summarised in this report, which is complimented by a more detailed review, submitted to an academic journal for peer review ([Safely recovering value from plastic waste in the Global South: Opportunities and challenges for circular economy and plastic pollution mitigation](#)).

**Table 1:** Approaches to recovering value from post-consumer plastic packaging waste

<b>Approach 1</b>	Conventional mechanical reprocessing for extrusion
<b>Approach 2</b>	Bottle-to-fibre mechanical reprocessing for extrusion
<b>Approach 3</b>	Mineral-polymer composites: road surfacing; brick and tile production
<b>Approach 4</b>	Solvent-based purification
<b>Approach 5</b>	Chemical depolymerisation (chemolysis)
<b>Approach 6</b>	Pyrolysis and gasification
<b>Approach 7</b>	Co-processing in cement kilns
<b>Approach 8</b>	Incineration with energy recovery

Each approach was assessed according to its impact on the environment; public and occupational health; and commercial prevalence and maturity. This enabled a further assessment of their suitability for implementation in low- and middle-income countries (LMICs) including the risk that they may be operated below safety standards. They were arranged into three groups (**Groups 1–3**) as shown in [Figure 1](#), according to their relative risks and/or the availability of evidence, the first of which is subdivided into two further sub-groups (**Groups 1a** and **1b**).

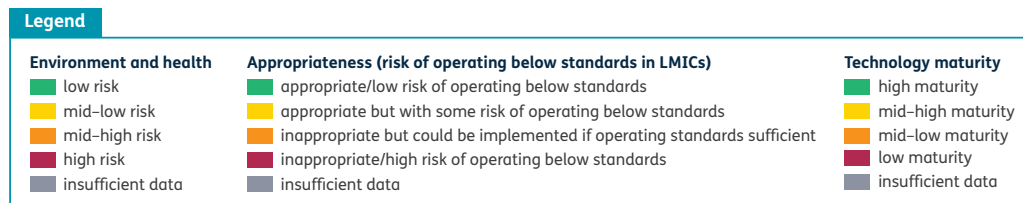
The mechanical reprocessing technologies in **Group 1a** are the least impactful on the environment and health, while being both mature and appropriate for implementation in LMICs, where they have been carried out at scale for at least 40 years. There are still some shortcomings with mechanical reprocessing, such as high loss rates, which can result in the mismanagement of residues. However, with improved management of feedstock and waste collection infrastructure these can be mitigated to an extent.



**Figure 1:** Summary of indicative environmental and health risks, and appropriateness for implementation in LMICs, for approaches to processing post-consumer plastic packaging waste generated by fast-moving consumer goods companies

**Abbreviations**

HICs - high-income countries  
LMICs - low- and middle-income countries



The approaches in **Group 1b** are appropriate for LMICs, though the limited supporting data and commercial nascence indicate that more research is required to evidence the health and environmental benefits. In particular, the risk exposure from plastic melt and low temperature combustion emissions is poorly understood. These technologies should be adopted cautiously in the short-term until planned further work has been carried out to evidence the potential risk to occupational and public health.

This report recommends that the approaches in **Groups 1a** and **1b** are prioritised above others (where appropriate and feasible) while putting in place appropriate support to enable smaller, less formal reprocessors to operate safely.

The ‘chemical recycling’ technologies in **Group 2** are immature and commercially unproven, which means that the relevant environmental and health evidence is too limited to assess with high certainty. All of the processes may involve heat, pressure, chemical solvents and potentially hazardous residues which result in a risk to human health if they are not carefully controlled. Anecdotally, there appears to be an increasing number of small-scale pyrolysis facilities in LMICs in recent years. Given the high risks of these technologies being operated below standards, it is recommended that FMCG companies avoid the use of these plants for processing their post-consumer plastic packaging waste unless they can publicly evidence their efficacy and safety.

The thermal processes in **Group 3** are not recycling and should not be used to process plastic packaging waste that has been collected for recycling. Plastic is a fossil fuel and should not be combusted to generate energy unless

it is mixed with other materials to the degree that it is technically and economically infeasible to disaggregate. The life cycle benefits of coal replacement are notable, however as countries decarbonise their energy supplies, these benefits will rapidly diminish.

This review finds no fundamental opposition to any technology on the grounds of public or occupational health in the right context. In theory, all of them can be operated safely, as long as sufficient engineering and management controls are in place. However, there is a serious risk that the technologies in **Groups 2** and **3** could result in serious harm to human health and the environment if operated in jurisdictions that do not have effective, well-resourced and independent regulation. It is therefore recommended that FMCG companies do not choose any of them to process post-consumer plastic packaging waste that has been collected for recycling unless this oversight and regulation can be guaranteed. Conversely the risks from approaches in **Group 1a** and **1b** are less concerning. Even if operated poorly, the risk of harm to people and the environment from the extrusion (or other melting) of post-consumer polyolefins and PET will be minimal compared to the thermal and chemical processes in **Groups 2** and **3**.

In all cases, FMCG companies should consider how they can put in place appropriate support to enable reprocessors to work towards implementing safety standards that are equivalent to those in Europe. Where there is insufficient capacity for regulators in LMICs to enforce these standards, FMCG companies should monitor adherence via independent auditors.

# Glossary of terms and abbreviations

## Terms

### Abiotic resource depletion

The depletion of non-biological (ie not plant- or animal-based) resources. Examples include metals, minerals and crude oil.

### Chain scission

Refers to the degradation of polymers in plastics where bonds in the main polymer chain are broken, making them shorter and reducing the mechanical durability of the plastic.

### Closed-loop recycling

The recovery and reprocessing of material that is used to manufacture items that can be recycled again without significant loss of properties (NB: this definition is offered here to assist with understanding however it is not used consistently in literature).

### Collected for recycling

In this context, 'collected for recycling' means plastic packaging waste that has been separated at source or recovered from residual waste and concentrated with the intention of recovering its material or chemical value.

### Comminution

Describes a collection of processes that reduce the size of materials through the action of shredding, shattering, grinding, pulverising or cutting.

### Depolymerisation

Involves breaking down polymers (large, long-chain molecules) into monomers (single repeating molecules that make up polymers) or oligomers (short chains of monomers, not long enough to be considered polymers).

### Ecotoxicity

The degree to which substances can cause harm to individual biota, assemblages, populations and ecosystems.

### Elementary flows

In life cycle assessment, the term 'elementary flows' refers to materials or energy being studied. Examples include chemical substances, electrical energy and minerals.

### Eutrophication

Occurs when a body of water becomes over-enriched with nutrients. Potentially, a plastics reprocessor handling highly food-contaminated material could discharge the food-rich wastewater into an aquatic compartment. The resulting over-enrichment can encourage growth of flora, often a single species, which can change the biological and chemical composition of the water, harming other species and causing species loss.

### Material circularity

A combination of actions, policies and decisions that enable and facilitate the recycling and/or transformation of materials into products that can in turn be recycled. The aspiration of a 'circular economy' is that these cycles take place with minimal loss of material and energy.

### Open-loop recycling

The recovery and reprocessing of material that is used to manufacture items that are unlikely to be recycled again due to loss of properties, or because they are part of assemblies or composites that are technically or economically challenging to disaggregate (NB: this definition is offered here to assist with understanding however it is not used consistently in literature).

### Process emission control

The term used to describe activities and engineered systems to control the emission of substances and materials into the environment.

### Raw material

A basic material that has undergone minimal processing which is used to manufacture goods. Examples include steel, plastics, aluminium and glass. Raw materials differ from ores and so called 'starting materials' in that they are ready for use in manufacturing.

### Recycling

Here we use 'recycling' to describe several steps (processes) in the waste material flow system that could include separation, collection, sorting, transportation and reprocessing. Explicitly, this definition excludes energy recovery through combustion and the conversion of materials into fuel. Though most waste sector stakeholders, laws and written standards agree on the definition of recycling, there are incidences where it continues to be ambiguously applied.

There is broad acknowledgement that new or existing approaches may be justifiably included in the definition as



long as combustion is not involved, including, for instance, chemical recycling (Ellen MacArthur Foundation, 2020; International Organization for Standardization, 2013).

The various global definitions of ‘recyclable’ and ‘recycling’ are summarised by the American Institute for Packaging and the Environment (2018).

### Single-use plastic

The term ‘single-use’ is defined as any item of packaging that is designed to become waste after being used once for its intended purpose. This means virtually all plastic packaging is ‘single-use’. The term should not be confused with ‘ephemeral use’, which indicates that the use phase is very short (disposable drinks cups, plastic straws and plastic carrier bags are all examples of ephemeral single-use products).

## Abbreviations

<b>BATs</b>	Best available techniques	<b>PET</b>	Polyethylene terephthalate
<b>BHET</b>	Bis(2-hydroxyethyl) terephthalate	<b>PP</b>	Polypropylene
<b>EBA</b>	Ethylene–butyl acrylate	<b>PS</b>	Polystyrene
<b>EVA</b>	Ethylene–vinyl acetate	<b>PVC</b>	Polyvinyl chloride
<b>FMCG</b>	Fast-moving consumer goods	<b>SBS</b>	Styrene–butadiene–styrene
<b>HDPE</b>	High-density polyethylene	<b>SEBS</b>	Styrene–ethylene/butylene–styrene
<b>HICs</b>	High-income countries	<b>SIS</b>	Styrene–isoprene–styrene
<b>LCA</b>	Life cycle assessment	<b>SRF</b>	Solid recovered fuel
<b>LDPE</b>	Low-density polyethylene	<b>TRL</b>	Technological readiness level
<b>LMICs</b>	Low- and middle-income countries	<b>USP</b>	Unique selling point
<b>PE</b>	Polyethylene		

### Starting material

In chemistry, starting materials are chemical substances that are used to create other materials via chemical reactions. In materials science, the term is used to describe any material that has undergone a physical, chemical or thermal process that renders it into a suitable state from which products or further materials can be created. Starting materials can be raw materials, chemical substances, or materials produced as a result of processing waste.

### System boundary

In life cycle assessment, a ‘system boundary’ is used to define which of the system components (processes and products) and flows are being assessed and which are not.

# 1 Introduction

Increasing concern about plastic pollution has resulted in a large number of policy approaches and interventions by governments, non-governmental organisations and commercial entities, aimed at mitigating the harmful effects of plastic waste when it interacts with the natural environment (da Costa et al., 2020; Provencher et al., 2020). As producers of large amounts of single-use plastic, fast-moving consumer goods (FMCG) companies have responded to the plastic pollution crisis with commitments that aim to increase material circularity. For instance, the Ellen MacArthur Foundation and UN Environment Programme (2020) have obtained signatures from more than 250 global businesses across the plastics value chain, committing them to a range of measures, such as eliminating avoidable plastic, making plastic items recyclable, and increasing the content of recycled material in new plastic products. Concurrently, several organisations, including Tearfund, have advocated for an overall reduction in plastic production in favour of alternative materials, reuse models and elimination of some products altogether.

Theoretically, the interventions that increase the circularity of plastics will increase the value of plastic waste and create an incentive to keep it out of the environment. Many millions of tonnes of plastic waste will need to be processed, requiring investment in infrastructure; increased separate collection; improved

sorting technology and practices; and the management of large amounts of residual material. This change will need to be managed without causing further damage to the environment, human health and the livelihoods of those who recover plastic waste for income – in particular, the informal recycling sector (waste pickers), whose participants are estimated to recover around 90 million tonnes of waste each year for recycling (Cook and Velis, 2020).

To assist with this rapidly evolving landscape, Tearfund (2020) has been working with stakeholders to develop a list of guidelines aimed at establishing fair partnerships between the informal waste sector and FMCG companies (hereafter the ‘Guiding Principles’). Although they are primarily focussed on maintaining equity in the value chain, the Guiding Principles also invite FMCG companies to commit to the ‘safe processing’ of plastic waste; a term that is yet to be defined and which is open to ambiguous interpretation by different stakeholders.<sup>1</sup> The aim of this report is to define the term and assess how it may be applied to eight different approaches (Table 2). These approaches were chosen following discussions between Tearfund and FMCG companies, which indicated that they are being considered or actively pursued as solutions to recovering value from post-consumer plastic packaging waste.

**Table 2:** Approaches to recovering value from post-consumer plastic packaging waste that has been collected for recycling

<b>Approach 1</b>	Conventional mechanical reprocessing for extrusion	<a href="#">Section 4.1</a>
<b>Approach 2</b>	Bottle-to-fibre mechanical reprocessing for extrusion	<a href="#">Section 4.2</a>
<b>Approach 3</b>	Mineral-polymer composites: road surfacing; brick and tile production	<a href="#">Section 4.3</a>
<b>Approach 4</b>	Solvent-based purification	<a href="#">Section 4.4</a>
<b>Approach 5</b>	Chemical depolymerisation (chemolysis)	<a href="#">Section 4.5</a>
<b>Approach 6</b>	Pyrolysis and gasification	<a href="#">Section 4.6</a>
<b>Approach 7</b>	Co-processing in cement kilns	<a href="#">Section 4.7</a>
<b>Approach 8</b>	Incineration with energy recovery	<a href="#">Section 4.8</a>

<sup>1</sup> Part G of Section 1 (Policy commitments) and part 2.9 of Section 2 (Programmatic commitments) of the Guiding Principles make reference to ‘safe end uses’ of recycled plastics.

## 1.1 Scope

The focus of this review is on ‘single-use’ plastic packaging, as it is the main group of plastics generated by FMCG companies which is at risk of being mismanaged.<sup>2</sup> Each of the eight approaches in [Table 2](#) will be assessed on the basis that they are used to process single-use post-consumer plastic packaging waste that has been ‘collected for recycling’.<sup>3</sup> This excludes assessment of approaches applied to processing post-consumer plastic packaging waste that has been mixed together with other materials; for instance incineration of ‘mixed municipal solid waste’ or the co-processing of ‘solid recovered fuel’ (containing non-plastics) in cement kilns.

Although this report assesses plastic packaging collected for recycling, several of the processes reviewed are not considered to be ‘recycling’ by the majority of the waste sector stakeholders, laws and written standards. For instance, incineration with energy recovery, co-processing in cement kilns, pyrolysis-to-fuel and gasification are all processes that are not compatible with the term ‘recycling’. In line with a review by the American Institute for Packaging and the Environment (2018), we use ‘recycling’ to describe several steps (processes) in the waste material flow system that could include separation, collection, sorting, transport and reprocessing, excluding energy recovery through combustion and the conversion of materials into fuel. There is broad acknowledgement that new or existing approaches may be justifiably included in the definition as long as combustion is not involved, including for instance chemical recycling (Ellen

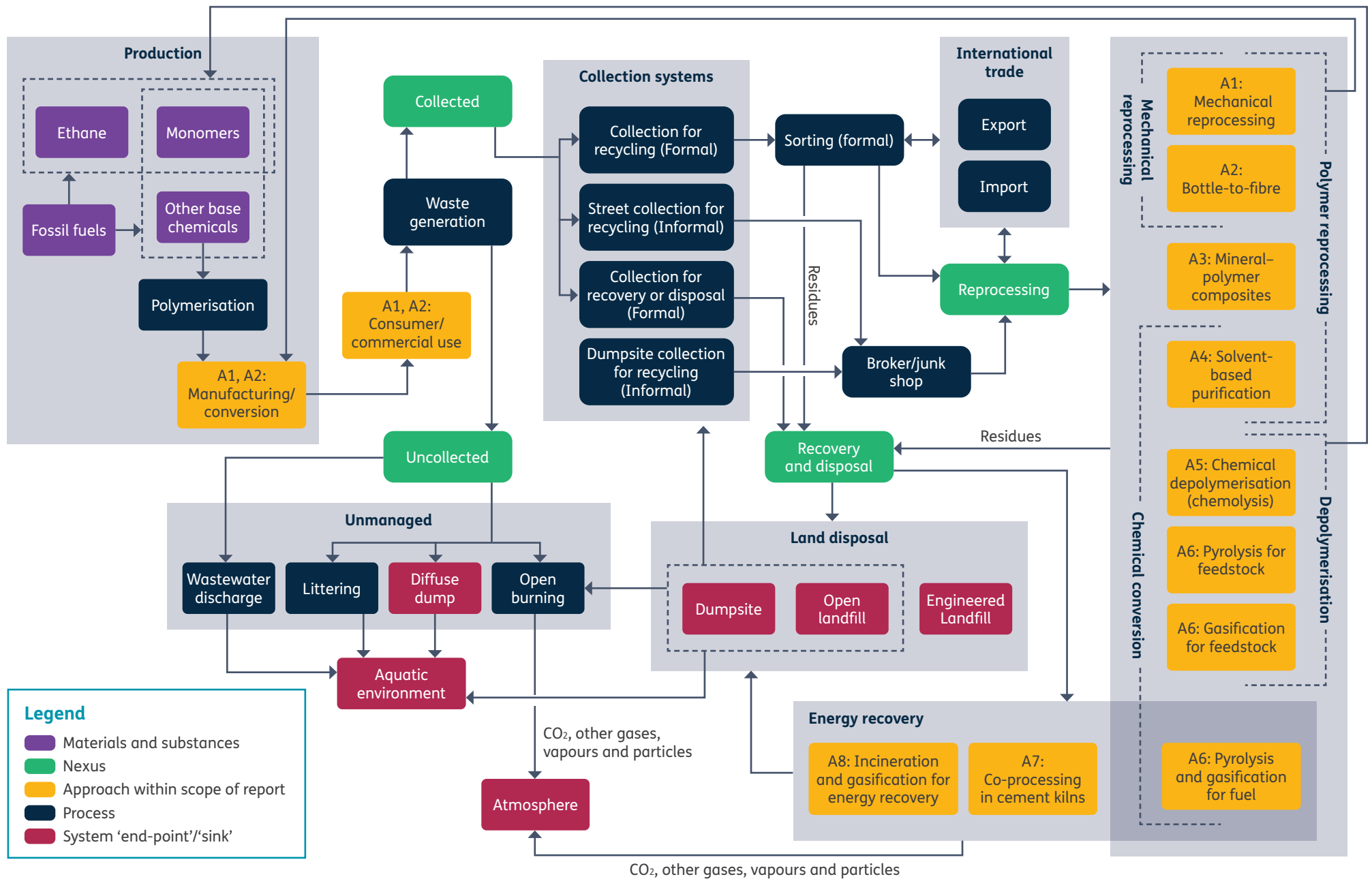
MacArthur Foundation, 2020; International Organization for Standardization, 2013).

Much of the evidence revealed in this review relates to high-income countries (HICs), however the emphasis of the findings and conclusions focuses on how this evidence relates to the low- and middle-income country context, where the majority of the world’s plastic waste mismanagement takes place (Kaza et al., 2018; Lau et al., 2020).

No approach to recover or reprocess post-consumer plastic packaging waste exists in isolation. Plastics flow through society via a complex system that involves many components and phases including production, use, end-of-life management and mismanagement. For most of the mass of plastic produced, the system is linear, with roughly 100 million tonnes of municipal solid waste plastic being disposed of each year and a similar quantity being mismanaged (Lau et al., 2020). A basic representation of this complex system is illustrated by the conceptual diagram shown in [Figure 2](#). The eight approaches are represented by the orange boxes marked **A1–A8**. Approaches **A1** and **A2** appear twice on the diagram. This is because the material system is circular, and there is a risk that substances, materials and biological agents are transferred into new products from a previous use phase or as a result of a waste management activity. Manufacturing/conversion and consumer/commercial use are therefore within the scope of Approaches **A1** and **A2**.

- 
- 2 The term ‘single-use’ is defined as any item of packaging that is designed to become waste after being used once for its intended purpose. This means virtually all plastic packaging is ‘single-use’. The term should not be confused with ‘ephemeral use’ which indicates that the use phase is very short. (Disposable drinks cups, plastic straws and plastic carrier bags are all examples of ephemeral single-use products.)
  - 3 In this context, ‘collected for recycling’ means plastic packaging waste that has been separated at source, or recovered from residual waste and concentrated, with the intention of recovering its material or chemical value.

**Figure 2:** Generalised material flow of plastic and plastic waste management in society, adapted from Cook et al. (2020), Hahladakis et al. (2018), Rollinson and Oladejo (2020) and Lau et al. (2020). Arrows denote flow of material mass unless specified otherwise. **A1–A8** represent the eight approaches detailed in [Table 2](#).



## 2 Method and structure of this review

This is a rapid review that summarises evidence from other reviews supplemented with literature obtained using snowball and citation search methods (Cooper et al., 2018). Most of the literature reviewed is academic because it is often more reliable, having undergone scrutiny from anonymous reviewers prior to its publication. Other, non-academic work has also been included where it appears sufficiently robust to warrant inclusion. For some topics, such as mechanical recycling, a review of multimedia evidence (YouTube) was carried out as a source of evidence if academic or grey literature was insufficient. A detailed method is provided in the [Appendix](#).

In [Section 3](#) the concept of safety is addressed alongside a discussion of some of the types of information that can be used to evidence it. [Section 4](#) summarises evidence across the eight approaches, discussing for each:

1. The prevalence and maturity (context);
2. The environmental benefits and impacts; and
3. The occupational and public safety challenges.

[Section 5](#) discusses the strength and availability of data and ranks the commercial maturity of each of the approaches ([Section 5.1](#)). In [Section 6](#), the approaches are assessed for the appropriateness for implementation in LMICs and then arranged into groups which simplify the state of knowledge and relative safety of each.

Separately, a more detailed review has been submitted to an academic journal that supports the evidence for the present study, and a copy has been uploaded to a preprint server ([Safely recovering value from plastic waste in the Global South: Opportunities and challenges for circular economy and plastic pollution mitigation](#)). The rationale for doing so is that, in addition to the academic review already carried out during this report's production, the underlying evidence and conclusions will be blind peer reviewed, strengthening their merit and rigor.



📷 A truck offloading plastic bottles at the site of a plastic bottle collecting company in Kinyamwezi. Photo: Daniel Msirikale/Tearfund

# 3 What does it mean to recover value from plastic packaging waste safely?

A fundamental rationale for waste management is to reduce the risk of potentially harmful substances, materials and biological agents from interacting with humans, animals, plants and the environment. Waste is either contained to prevent that interaction or transformed so that it becomes less harmful. For example, landfills are used to ‘contain’ harmful waste and composting plants are used to ‘transform’ biological waste to reduce its bioactivity.

Sometimes the act of containing or transforming waste may result in additional challenges. For instance, modern landfills can be designed to contain waste effectively, but the conditions they facilitate still result in the production of methane when biological material breaks down without oxygen. Similarly, incinerators use combustion to reduce the hazardousness of (transformed) waste, but also produce potentially harmful gases and particles that must be controlled to prevent harm to people, animals, plants and the environment.

When plastic waste is emitted into the environment through burning, dumping or accidental release, it can cause harm to animals, plants and people (Cook and Velis, 2020). To prevent this, we can collect, contain or transform plastic waste into useful products, such as secondary raw materials (recycled plastic), chemical substances (eg monomers), heat or fuel. The processes used to carry out these transformations involve breaking plastic into smaller pieces (comminution), heating, applying pressure, or even using solvents to break down or purify the constituent polymers. Surprisingly or not, these processes result in the emission of substances and particles, both from the plastics as they are transformed, and also through the generation of power to carry out the transformations. This review seeks to determine whether the risk of harm from these emissions outweighs the benefits of recovering energy or materials from the plastics.

## Basel convention on the control of transboundary movements of hazardous wastes and their disposal (Article 2, No. 8)

*“Environmentally sound management of hazardous wastes or other wastes” means taking all practicable steps to ensure that hazardous wastes or other wastes are managed in a manner which will protect human health and the environment against the adverse effects which may result from such wastes.’*

UNEP and Basel Convention, 2020a

No guidance exists that assesses the relative or absolute safety of the eight approaches reviewed in this report. An open-ended working group of the Basel Convention (nd)<sup>4</sup> has made some progress by drafting a review (UNEP and Basel Convention, 2020b) of ‘environmentally sound management’ of plastics, a phrase used in recent amendments to the Convention (UNEP and Basel Convention, 2020a). The review is comprehensive and covers many aspects of plastic management, though it does not compare and assess the relative safety of the processes.

Three concepts are used to ‘test’, assess and compare the relative safety of each of the eight approaches which are discussed in the following subsections:

1. Prevalence and maturity (context) ([Section 3.1](#));
2. Environmental benefits and impacts ([Section 3.2](#)); and
3. Occupational and public safety challenges ([Section 3.3](#))

These three tests are applied to each approach throughout this report, and then used to qualitatively assess their appropriateness for processing plastic packaging in LMICs.

<sup>4</sup> Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal

### 3.1 Prevalence and maturity

The maturity and prevalence of a process or approach can indicate how certain we are that it is safe or effective. A good example in the waste management sector is landfill, which has been the most prevalent approach to managing municipal solid waste for millennia (Rodríguez, 2012). Landfill engineering has evolved substantially over the last century, and our ability to manage its negative effects on the environment has improved. We are able to engineer more effective liners, caps and pollutant capture equipment; landfill structures can be made stable. Containing and treating emissions from landfills is still a challenge. Landfill is still considered to be the least favourable method of waste management, and many governments and regions have committed to phase it out.<sup>5</sup> But, given that we have built so many landfill sites, our experience with the approach is very significant. Thus, we can be reasonably certain about how much landfills will cost to build and operate, as well as their environmental benefits and drawbacks.

By contrast, we have less certainty when it comes to newer technology. The less process data that exists, the less certain we can be about how much energy will be used, what pollutants will be emitted, or how commercially viable an approach may be across the life cycle. This is particularly important for nascent processes such as those described under the umbrella of ‘chemical recycling’ (Approaches 4, 5 and 6 in this report). However, even with more established processes, such as the mechanical recycling of plastics, there have been substantial market failures. Though mechanical recycling

of plastics has been implemented commercially in LMICs since at least the 1980s, when it was introduced at scale in HICs in the 2000s, many plants failed to maintain commercial viability (Lerpiniere and Cook, 2018).

Operators of newer technology may be concerned about sharing process data, either because their process works well and they want to monopolise the market, or because it doesn’t and they want to attract investment to improve it. Occasionally, innovators may obfuscate the truth because their process will never work, but they still want to attract funding (Hindenburg Research, 2020; Straker et al., 2021). It is therefore understandable that there is little process information for some newer technologies.

Where process data have been published, the methods for attaining data are transparent, and conflicts of interest do not interfere with the findings, we are able to assess, compare and objectively criticise. But it is much more challenging to evaluate nascent innovations, so there is greater uncertainty about how they will perform in a commercial context and what risks they pose to human health or the environment. In this report, we will discuss the relative maturity of the approaches and summarise evidence that indicates their prevalence as commercially proven processes. The purpose of this part of the assessment is not to quash or neglect data from new innovations, but to build up a picture of how certain we are that a process is going to help us reduce plastic pollution, rather than exacerbate it through unwanted emissions.

### 3.2 Environmental safety

Plastics result in a range of environmental impacts, including CO<sub>2</sub>eq emissions during production, reprocessing or combustion; debris/particle emissions to marine and terrestrial environments during all life cycle phases; abiotic resource depletion as a consequence of plastics production; and chemical substance emissions during both production and through migration during all subsequent phases (Nielsen et al., 2020). According to Zheng and Suh (2019), global plastic production is estimated to contribute approximately 1.7 billion tonnes of CO<sub>2</sub>eq emissions. This is projected to increase to 6.5 billion tonnes of CO<sub>2</sub>eq by 2050.<sup>6</sup> Conversely, plastics can result in many environmental benefits, due to their high utility in

comparison to other materials and their ability to protect more valuable substances and materials that would otherwise become damaged or destroyed (Andrady and Neal, 2009; Bisinella et al., 2018; Edwards and Fry, 2007; Franklin Associates, 2018).

Life cycle assessment (LCA) is the most developed approach for quantifying and comparing environmental emissions. However, it has been criticised for inconsistencies between the use and reporting of elementary flows (Edelen et al., 2018); inconsistently chosen system boundaries (Tillman et al., 1998);<sup>7</sup> outsourcing beyond a system boundary (Klöpffer and

5 Here, ‘waste management’ excludes self-management, for example through open burning and open dumping which are more damaging than landfill.

6 Based on a counterfactual scenario in which the current global energy generation mix would remain static.

7 The choice of where to place the system boundary can strongly affect the outcome of a study. For instance, an assessment of the impact of wind turbines that negated energy generation during the use phase would ignore the fossil energy avoided during its life; showing that wind turbines harm the environment. Sometimes an apparently subtle choice to include or exclude certain system components can substantially impact the outcome of a study. Care should be taken when comparing life cycle assessment studies that have inconsistent system boundaries because they are comparing different systems.

Grahl, 2014); and inconsistent emission factors,<sup>8</sup> which can vary according to the source or software used and which can impact on the outcome of a particular study (Jain et al., 2015; Rajendran et al., 2013). Moreover, LCA studies usually omit data on waste mismanagement. For instance, Zheng and Suh (2019) reported that CO<sub>2</sub>eq emissions from the end-of-life phase are just nine per cent of the total. However, as with many LCA studies, they did not assess the impact of plastic waste when it is burned in open, uncontrolled fires, which could be as much as 49 million tonnes per annum (Lau et al., 2020). This mass could result in many millions of tonnes of additional CO<sub>2</sub>eq, far more than the production phase (Gower et al., 2020; Reyna-Bensusan et al., 2018; Wiedinmyer et al., 2014).

Despite its shortcomings, LCA is still the most widely reported approach for evidencing and comparing the

environmental impacts of anthropogenic processes, activities and the production of materials. In this report, we will present short summaries of LCA-derived information alongside narrative which aims to highlight uncertainties and potential omissions from the presented data. However, it is not within the resources of the present study to provide an overall quantitative assessment of the environmental benefits and drawbacks of any particular treatment pathway in the context of the wider global system. Though much of the data reported are commensurate with the European Waste Hierarchy (European Commission, 2008),<sup>9</sup> the framework is deliberately not referred to as it is not always supported by all studies. Instead, a specific qualitative assessment of each approach is provided.

### 3.3 Occupational and public health

Globally, the waste management sector has a historically poor record for accidents and ill-health (Doherty, 2019). This is most acute in LMICs where the resources to comprehensively mitigate harm to human health are not always sufficient. Most of the evidence reviewed in this report comes from HICs, because the same lack of resources in LMICs means that health and safety data are also scant. The assumption is made that the control of hazard exposure correlates with the resources available to control them, the level of regulatory oversight and the capacity to enforce regulation. If FMCG companies aspire to protect occupational and public health, this

report will highlight some of the hazards and risks that they may need to be aware of to ensure full duty of care for the processing of materials they place on the market. Importantly, it is not within the resources of this rapid review to present a comprehensive assessment of health and safety risk within each of the eight approaches. There are likely to be lots of others not covered, and these would make an interesting topic for a much larger study. Instead, this study has aimed to summarise the data available to assess the general standard of risk management likely to be experienced in different contexts.

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<sup>8</sup> Life cycle assessment studies are often carried out using proprietary databases that contain information used to calculate the emissions of energy, substances and materials from different processes within the system being studied. Variation on the choice of factors has the potential to substantially impact on the results of a study.

<sup>9</sup> The Waste Hierarchy is not only used in Europe, although this paper refers to it specifically for consistency as it has a clearly outlined and demarcated set of definitions.



# 4 Approaches to managing plastic packaging waste

## 4.1 Approach 1: Conventional mechanical reprocessing for extrusion

### 4.1.1 Overview

Mechanical reprocessing of waste plastics is now a relatively mature technology, having been carried out in LMICs since at least the 1980s and 1990s (Lardinois and Klundert, 1995; Wahab et al., 2007). Facilities range from extremely simple operations that involve basic manual contaminant removal, followed by melting and re-extrusion, through to extremely complex operations involving multiple steps aimed at purifying and concentrating plastic, removing surface contamination and other non-plastics using sophisticated equipment (Schyns and Shaver, 2020). In LMICs there is a huge and diverse range of facility types and scales across many different countries and cultures, from extremely rudimentary back-yard operations through to large-scale commercial facilities that contain a multiplicity of unit processes. In general, mechanical reprocessing plants in these countries often rely on manual separation, though very little process data is available in the scientific literature, leaving a conspicuous gap in our understanding and hence our ability to assess the safety risks of these processes to the environment or human health.

The evidence for how plastics reprocessors operate in HICs is reasonably well documented, though commercial sensitivity sometimes obscures the latest developments. Manual sorting is slowly being replaced as optical separation technology increases in accuracy and many modern plants have reported to reduce their material losses considerably as their processes and learning mature. Plants tend to be larger in HICs as operators exploit the economy of scale (Lerpiniere and Cook, 2018). Though many plants in these countries struggled to maintain commercial stability during the early part of the 21st century, in 2020, the mechanical recycling business appears to be booming, encouraged by government policy and voluntary commitments from businesses that promise to increase demand for secondary material.

### 4.1.2 Environment

#### Global warming potential

Overwhelmingly, LCA studies indicate that mechanical recycling for extrusion is associated with net environmental benefits compared to all other treatment options (Bernardo et al., 2016; Lazarevic et al., 2010).<sup>10</sup> Very few LCAs investigate reprocessors operating in LMIC context, meaning that process data are absent for these facilities (Laurent et al., 2014). A few exceptions (found in a non-exhaustive search) exist for China (Gu et al., 2017; Zhang et al., 2020), India (Aryan et al., 2019; Choudhary et al., 2019) and Brazil (Martin et al., 2021). It is possible that smaller scale, simpler or dry operations result in lower environmental impact compared to some processes in HICs. For instance, the relative benefits of recycling based on lower-tech operations in India highlighted by Aryan et al. (2019) showed very low emissions from mechanical recycling compared to all other forms of treatment, with a considerably greater gap than would be expected in an HIC despite the direct use of coal to heat water and dry flake.

More attention should be paid to gathering and assessing processes in LMICs for which robust studies are largely absent. However, mechanical reprocessing is still likely to be the least impactful method of processing in comparison to all other processes.

#### Water use

The way water is used and discharged should also be carefully considered by FMCG companies who are considering processing their packaging by conventional mechanical reprocessors, especially in areas of water scarcity. Though some plants are entirely dry, those that use water can consume between 340 and 452 litres per tonne of plastic waste processed (Chen et al., 2019). Of this, between 65 and 95 per cent becomes wastewater. Highly contaminated plastics can result in much higher water use, around 1,200–1,600 L t<sup>-1</sup> plastic waste processed as reported by Aryan et al. (2019). If wastewater isn't treated correctly it can contribute to

<sup>10</sup> There is some indication that where plastics are heavily soiled, the energy used to clean them increases emissions beyond those emitted during incineration with energy recovery. But the evidence is scant, and therefore further research is needed to find out how critical this aspect of processing is to the environmental impact. The impact of incineration with energy recovery is lessened only because of its displacement of electricity generation by coal; plastics are still fossil fuels. Therefore, as energy grids decarbonise over the next century, the case for mechanical recycling is likely to improve substantially.

freshwater aquatic ecotoxicity, marine aquatic ecotoxicity and eutrophication. FMCG companies should ensure that plants processing their material incorporate both water recirculation and effective wastewater treatment before discharge.

### Management of residues

Though there is no consolidated and systematic scientific evidence of the practice, the mismanagement of plastic residues<sup>11</sup> by plastics reprocessors in LMICs has been acknowledged by multiple national governments (Liang et al., 2021; Secretariat of the Basel Convention, 2019) and evidenced in multimedia (60 Minutes Australia, 2019; BBC News, 2020; CBC News, 2019; Sky News, 2018). Around 50 per cent of mixed plastic packaging is at risk of mismanagement, being of low value or of a concentration too low to economically separate (SYSTEMIQ and The Pew Charitable Trust, 2020). In countries that lack well-resourced and effectively enforced waste management regulation, the risk of these residues being dumped on land, in the aquatic environment or being burned is considerable (Velis and Cook, 2021). All are potential pathways which pose serious harm to the environment and human health.

It is also likely that plastic pellet and fragment loss from reprocessing in LMICs makes a proportionally small but significant contribution to microplastic pollution. Most studies relate to HICs (Boucher and Friot, 2017; Cole and Sherrington, 2016; Lassen et al., 2015), however this review found observational multimedia evidence of several plants where plastic debris emission appeared to be poorly controlled (Potdar, 2015; Saha, 2020; Singh, 2018; sps, 2018b; Triwood1973, 2009).

To ensure that FMCG companies do not contribute further to residue mismanagement and plastic pellet and fragment loss to the environment, it is recommended that reprocessors handling FMCG post-consumer plastic waste operate a policy of zero discharge to the environment (as far as is reasonably practicable) that is independently monitored and audited by a third party, for instance Operation Clean Sweep (2020).

## 4.1.3 Health

### Occupational risk during plastic reprocessing

The main plastics (polyolefins and PET) used in packaging pose few threats to human health through emission of hazardous substances during extrusion if managed with adequate mechanical ventilation or dilution (Cook et al., 2020; Unwin et al., 2013). However, extrusion of both PVC and polystyrene (PS) in an environment without engineering controls may expose workers to high

concentrations of volatile organic compounds (He et al., 2015). Contaminants from the previous use phase, for instance where non-packaging materials are co-processed with packaging, could expose workers to substances of concern, such as brominated flame retardants and phthalates (Tang et al., 2014; Tang et al., 2015; Tsai et al., 2009). To minimise risk to workers and residents living nearby to plastics reprocessing facilities, FMCG companies should ensure that reprocessors receiving their materials implement stringent procedures to trace the origin of all input materials as well as sufficient atmospheric emission controls.

Multimedia evidence of a variety of workplace hazards in LMICs revealed instances of exposure to fast-moving, high-torque or hot machinery, and caustic substances (Daharwal, 2018; IndustrieS, 2019; Kumar, 2019; Micro Machinery Manufacture, 2018; Mooge Tech., 2015; Potdar, 2015; Saha, 2020; Singh, 2018; sps, 2018a; sps, 2018b; The Times of India, 2019; Triwood1973, 2009). Though two examples of plants were identified which appeared to be managed safely (Carretino Proyectos, 2016; Kao, 2014), the majority lacked PPE for workers and any evidence of safe systems of work. To ensure that occupational or public health is protected as far as reasonably practicable, it is recommended that FMCG companies put in place appropriate support to enable reprocessors to work towards implementing safety standards that are equivalent to those in Europe. Where there is insufficient capacity for regulators in LMICs to enforce these standards, FMCG companies should monitor adherence via independent auditors.

### Food contact applications and legacy substances

The use of secondary plastics in new food contact packaging is tightly controlled in many countries and banned in others because of the risk that potentially hazardous substances from the previous use phase may be inherited into material used in new products (Ministry of Health and Family Welfare, 2018; PackagingLaw.com, 2020; Rosato, 2020). Possibly, these so-called 'legacy substances' (Wagner and Schlummer, 2020), may occur at very low levels in all secondary plastics. There is some evidence that legislation and enforcement to prevent this inherited contamination are not always sufficient to protect human health in HICs and several have been detected in food contact packaging and toys, albeit at low concentrations (Cook et al., 2020).

Several countries permit the use of secondary plastics in food contact materials including Mexico (PetStar, 2018), South Africa (Petco, nd), and Brazil (PackagingLaw.com, 2019). However, in countries where this is not possible, legislation can represent a barrier for FMCG companies who have made commitments to recycle material into food contact packaging. It appears that

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11 Here, 'plastic residues' describes the fraction of plastic waste that is collected for recycling but which is too diverse or un-concentrated to be economically recoverable. For instance, rigid PET, HDPE and PP often make up the bulk of a mixed plastic packaging load by weight and are hence more commonly recycled. The various films, bags and polystyrene yoghurt pots will occur less frequently and are much more challenging to separate, clean and purify. Therefore, these will often be discarded as 'residues'.

several governments have relaxed, or may be preparing to relax, legislation to allow greater circularity and risk-based management of substances of concern inherited from the previous use phase (PackagingLaw.com, 2020; Rosato, 2020). To prevent the contamination of secondary products with legacy substances of concern,

it is recommended that FMCG companies ensure that extruders processing their packaging implement stringent procedures to trace the origin of all input materials and ensure that they are processed separately from non-packaging plastics.

## 4.2 Approach 2: Bottle-to-fibre reprocessing

### 4.2.1 Overview

Bottle-to-fibre reprocessing involves broadly similar processes to conventional mechanical reprocessing for extrusion. The input is PET plastic (usually bottles) and the output is polyester yarn for processing textiles. Of the 55 million tonnes of polyester produced in 2018, approximately 7.2 million tonnes (13 per cent by weight) was produced from post-consumer PET bottles and post-industrial spun PE fibre (Textile Exchange, 2019). The proportion of recycled content in polyester increased steadily over the previous decade, though it dipped slightly by three percentage points following the Chinese import ban on plastic waste (Ministry of Ecology and Environment, 2017), highlighting the impact of international restrictions on the circular economy. Back in 2008, polyester spinning was estimated to absorb just over 70 per cent of the PET collected for recycling (Park and Kim, 2014) whereas this proportion had reduced to approximately 44 per cent in 2016, as increasing quantities of material were being used in packaging applications (Sarioğlu and Kaynak, 2018). Bottle-to-fibre technology is mature, having been implemented since the 1990s (Patagonia, nd) and there is some evidence that the process improves the strength of the polymer (Muslim et al., 2016) in comparison to bottle-to-bottle applications where some chain scission may result in a loss of mechanical properties (Shen et al., 2010).

### 4.2.2 Environment

#### Global warming potential

Though there is little research that evidences the life cycle impacts of bottle-to-fibre recycling, the few studies that exist indicate that it performs equally or better than the so-called 'bottle-to-bottle' approach (Komly et al., 2012; RDC-Environment, 2010; Shen et al., 2011). Critics have highlighted the non-recyclability of the resultant textiles, with little opportunity for material circularity following the first use phase cycle. Thus, bottle-to-bottle recycling is often described as 'closed-loop' whereas bottle-to-fibre is often considered to be 'open-loop' recycling. However, Geyer et al. (2016) provides a convincing argument that refutes the assumption that closed-loop recycling is necessarily more environmentally sustainable than open-loop approaches such as bottle-to-fibre. Although bottle-to-bottle displaces virgin material production, bottle-to-fibre recycling displaces virgin PET production and cotton production, which generates twice as much

carbon (5.2 and 57.9 tonnes CO<sub>2</sub>eq per tonne) (Wang et al., 2015) as virgin polyester (2.2–2.7 tonnes CO<sub>2</sub>eq per tonne) (Bartl, 2020).

The energy source and national context are also key determinants of the overall life cycle benefits. To demonstrate this, two recent studies examining the impact of the Chinese import ban are relevant because prior to the restrictions, virtually all of the 2.5 million tonnes per annum of PET imported into the country was recycled into polyester fibre (Ma et al., 2020; Ren et al., 2020). Ren et al. (2020) highlighted that virgin polyester fibre produced in China resulted in a high global warming impact because electricity production in China is mainly coal-fired. By contrast, PET (or polyester fibre) produced in many HICs results in lower emissions because electricity is produced by gas, nuclear or renewable energy.

#### Water use

No data on water use was available to compare bottle-to-fibre with bottle-to-bottle recycling. Virgin polyester spinning is estimated to consume between 24.2 cubic metres of water per tonne (Zhang et al., 2018) and 48.8 cubic metres of water per tonne (Bartl, 2020) (excluding printing and dyeing). Possibly a more important comparator is for cotton which has been reported to use between 2,000 and 27,000 cubic metres of water per tonne in production (Bartl, 2020). Otherwise, there is no reason to assume that bottle-to-fibre reprocessing has a different water consumption rate in comparison to bottle-to-bottle.

#### Management of residues

No specific evidence was found to indicate microplastic release or residue mismanagement from bottle-to-fibre reprocessing, however it is reasonable to assume that it is a similar order of magnitude to conventional mechanical reprocessing.

#### Microplastic fibre release

It is beyond the scope and resources of this project to investigate the impact of microplastic fibre release from polyester fibres during the use phase, though future researchers may wish to consider this factor when assessing the use of polyester in comparison to other textile fibres.



Turning plastic waste into an economic opportunity – Kinshasa, DRC – Tearfund is co-implementing the project with the Church of Christ in Congo (ECC – Eglise du Christ au Congo). Photo: Flot Mundala/Tearfund

### 4.2.3 Health

No evidence that has not already been discussed in [Section 4.1.3](#) was found to indicate specific health hazards from polyester spinning. However, objective reasoning

suggests that the use of only one polymer (PET) in bottle-to-fibre reprocessing that is mainly used in packaging may lower the risk of contamination from materials that have been used in other applications, for instance end of life vehicles or electrical equipment.

## 4.3 Approach 3: Mineral–polymer composites

### 4.3.1 Overview

#### Road surfacing

Road surfacing has been promoted as a solution to finding uses for otherwise difficult to recycle plastics (Chin and Damen, 2019), an application that appears to have been embraced in India in recent years (Karelia, 2018; Louise, 2019; National Rural Roads Development Agency, nd; News18, 2019). It's worth clarifying that the use of plastics in road surfacing does not refer to a surface constructed entirely from plastic, but the modification of the bitumen to enhance its properties (RAHA Bitumen Co., nd). The practice of 'bitumen modification' has been investigated since the 1950s and has been in common use since the

1980s (Zhu et al., 2014). Since then, multiple reviews and experimental studies have highlighted considerable benefits that plastics bring to the properties of asphalt, such as reduced rutting, fatigue resistance, reduced thermal cracking, and increased elasticity (Ahmadinia et al., 2011; Chin and Damen, 2019; Costa et al., 2013; Dalhat and Al-Abdul Wahhab, 2017; Fang et al., 2014; Movilla-Quesada et al., 2019; Vasudevan et al., 2012; White, 2019; White and Reid, 2018; Wu and Montalvo, 2021).

Typically, five per cent (or around two to ten per cent) of the mass of bitumen is substituted with polymers (Rødland, 2019), but figures of up to 25 per cent have been reported (Giavarini, 1994). This means that only a very small proportion of the overall road surface is comprised

of plastic. Common virgin polymers used to modify bitumen include:

- polyethylene (PE)
- polypropylene (PP)
- ethylene–vinyl acetate (EVA)
- ethylene–butyl acrylate (EBA)
- styrene–butadiene–styrene (SBS)
- styrene–isoprene–styrene (SIS)
- styrene–ethylene/butylene–styrene (SEBS)

(Zhu et al., 2014).

## Bricks and tiles

Waste plastics can be used as a bonding agent for minerals through a process advocated by several charities, including WasteAid UK (Lenkiewicz and Webster, 2017). There are several proprietary and open-source processes available (Earth Titan, 2019). The process involves melting plastic together with sand to form a paste which is then pressed into moulds and left to cool. The resultant product has been reported to have greater compressive strength than Portland cement sandcrete (Kumi-Larbi et al., 2018). Several recent articles have investigated and reviewed the mechanical performance of plastic mineral composites for brick and tile production (Ali et al., 2020; Salvi et al., 2021; Thorneycroft et al., 2018; Uvarajan et al., 2021), however this topic does not appear to be well studied in the literature. A review of multimedia evidence (YouTube) found processes with varying sophistication and mechanisation from simple melting over a fire, to the use of mechanical pressurised moulding, mechanical mixing and comminution of plastics with low-speed, high-torque cutting mills (Earth Titan, 2019; Kolev, 2019; NTVUganda, 2013).

## Dry aggregate in concrete

Gu and Ozbakkaloglu (2016) reviewed 83 studies that investigated the use of plastics in concrete as a lightweight replacement for aggregate. Although it was not within the scope of this review to assess this end-use, it is referred to here to identify it as a potential avenue of further research.

### 4.3.2 Environment

#### Road surfacing (polymer-modified bitumen)

Despite the paucity of strong evidence, it appears that polymer modified bitumen is more durable than conventional bitumen, resulting in reduced global warming potential (Mukherjee, 2016; Nascimento et al., 2020; Poulidakos et al., 2017; Santos et al., 2018; Vila-Cortavitarte et al., 2018). Many of the studies reviewed lack critical components, such as system boundaries and transparent methodologies, and one, by Mukherjee (2016), did not consider the use phase.

Only one study indicated microplastic emissions from polymer modified roads, mainly through the use of studded tyres for stability while driving through ice (Vogelsang et al., 2020). The study acknowledged tremendous uncertainty in the emission factors it used but indicated emissions in Norway from polymer modified asphalt of just 28 tonnes per annum compared to 4,250–5,000 tonnes per annum from tyres.

There is far too little data available to make an assessment over whether the use of waste plastics as a bitumen modifier provides overall environmental improvement across the life cycle. Intuitively, anything that reduces the need to resurface or replace roads using a product that would otherwise be wasted ought to provide some benefit. However, the nuances of the system must be investigated thoroughly before such conclusions can be drawn.

Without any supporting evidence, it is suggested here that in some LMICs, waste plastics may be used in road surfacing primarily as a method of disposal, rather than to increase durability. A potential risk is that the surface may become less durable if asphalt-polymer mixtures are incorrectly formulated, for example if they are made too rich in polymer. It is recommended that this theory is investigated as lack of durability could influence both life cycle emissions and the risk of plastic particle emissions.

#### Brick and tile production

No data was found to evidence CO<sub>2</sub>eq emissions from mineral–polymer composites used in the production of bricks, tiles or paving slabs. As this technology begins to increase in prevalence, it will be important to understand the full life cycle impacts. Clearly, the low-tech processing advocated by WasteAid uses very few resources. The removal of plastic film would benefit the local environment – though the process requires relatively clean sand which would need to be sourced sensitively and sustainably. The LCA case is likely to be strongly driven by the avoided concrete production which is very energy-intensive (discussed further in [Section 4.7.1](#)), but it is noteworthy that the heat needed in the process may be provided by open, uncontrolled fires. Therefore, the climate change impact of black carbon production may also have a significant effect on the overall environmental emissions.

No evidence was found to indicate microplastic production during the use phase, and it is strongly suggested that this is considered in future investigations.

### 4.3.3 Health

Though polymer modification of bitumen is well established, it has thus far been carried out mainly with non-packaging plastics and rarely with waste plastics. Tile and brickmaking with waste plastics is less established. The risks to human health from both processes are likely to be from emissions of hazardous substances, released

when plastics are heated (He et al., 2015; Tsai et al., 2009; Yamashita et al., 2009) – but both processes can be conducted outside, and with adequate ventilation, these are likely to pose little risk to the operators. The risk is even lower when packaging plastics are used, partly because food contact material producers tend to avoid the use of harmful substances that can contaminate food, and because polyolefins and PET (the main packaging plastics) do not generally result in hazardous emissions when heated. However, where material provenance is uncertain or where material is known to come from applications such as end of life vehicles or electrical goods, the risk of exposure to potentially hazardous substances increases (Cook et al., 2020).

Where plastics briefly combust, as has been detected in some examples, the emission profile will be different again, and other products of incomplete combustion may be emitted (Barabad et al., 2018; Valavanidis et al., 2008; Wang et al., 2004). Kumi-Larbi Jnr (personal communication 10 December 2020) has planned some laboratory testing of melted and combusted LDPE sourced from West Africa. At the time of writing the testing has been delayed due to COVID-19.

With both asphalt modification and tile-making, workplace risks exist, including becoming entrained in high-speed or high-torque machinery, and having contact with hot materials as they are formed and moulded to the shape of the tile or road surface.

## 4.4 Approach 4: Solvent-based purification

### 4.4.1 Overview

Unlike other ‘chemical recycling’ processes, ‘solvent-based purification’<sup>12</sup> uses solvents to dissolve polymers, allowing them to be separated from the additives and contaminants found in the source plastics (Ügdüler et al., 2020). Part of the attraction of solvent-based purification is that it keeps most of the polymer chains intact, compared to mechanical recycling where heat causes some material degradation. Solvent-based purification may also be effective at delaminating and isolating plastics used in multi-layered, multi-material packaging, such as food and drink cartons (eg Tetra Paks) (Kaiser et al., 2018; Walker et al., 2020), and at separating the plastic fraction of textiles (Thiounn and Smith, 2020), for instance in polyester cotton mixtures (Sherwood, 2020).

Crippa et al. (2019) and Ügdüler et al. (2020) agree that no commercially viable solvent-based purification facilities are currently operational with the exception of CreaSolv® and Newcycling® technologies that Ügdüler et al. (2020) believes are at TRL 8–9, meaning they are close to commercialisation.<sup>13</sup> In 2018, Unilever (nd) opened a pilot plant in Indonesia capable of processing three tonnes of water sachet waste per day (1,000 tonnes per annum) using the CreaSolv® process (CreaCycle GmbH, nd). The company states an ambition to develop a plant processing 30,000 tonnes per annum, although it is unclear whether the plant can be proven as commercially viable to this level.

According to Zhao et al. (2018), the main challenge with commercialisation of solvent-based purification is the difficulty of removing solvents from the polymers and disposing of them economically.

### 4.4.2 Environment

Solvent-based purification has been reported as having the potential for high environmental performance coupled with low global warming impact. However, there is very little real world process data available (Crippa et al. 2019), and as it is yet to realise commercialisation, it would be disingenuous to report and extrapolate environmental performance data. Ügdüler et al. (2020) carried out a basic LCA of two processes to remove additives, though the work was highly theoretical and it would be misleading to extrapolate further.

### 4.4.3 Health

No studies have reported the health effects of solvent-based purification, though the greatest concern is the use of potentially hazardous solvents such as chloroform, xylene, n-hexane and cyclohexane (Ügdüler et al., 2020) – substances already known to cause harm. Anyone developing solvent-based purification technology will need to ensure that these substances can be removed from secondary plastics and rendered safe, to ensure that they do not risk human exposure when discarded, or due to their occurrence in recycled products containing solvent-recovered plastics.

12 Solvent-based purification is categorised under the broader term ‘chemical recycling’. This term is applied inconsistently. Some authors have argued that solvent-based purification should not be classified as chemical recycling because the polymers are not completely deconstructed, and it should instead be classed as mechanical recycling (Crippa et al., 2019). The author of the present study has no preference for which classification is more appropriate.

13 Technological readiness levels are used to describe the stages of innovation that an invention or idea has achieved. There are many variations, but broadly they are described according to the following nine levels: TRL1, Basic principles observed; TRL2, Technology concept formulated; TRL3, Experimental proof of concept; TRL4, Technology validated in lab; TRL5, Technology validated in relevant environment; TRL6, Technology demonstrated in relevant environment; TRL7, System model or prototype demonstration in operational environment; TRL8, System complete and qualified; and TRL9, Actual system proven in operational environment.

## 4.5 Approach 5: Chemical depolymerisation (chemolysis)

### 4.5.1 Overview

This group of processes involves reacting plastics with various substances (catalysts, acids, alkalis or alcohols) under heat and pressure to depolymerise the polymers (Raheem et al., 2019). Roughly seven process groups have been reported under the 'depolymerisation' category (Kumar et al., 2011; Ragaert et al., 2017; Raheem et al., 2019), but the technology is only commercially proven for the glycolysis of polyester (Ragaert et al., 2017)<sup>14</sup> and the chemolysis of polyamide (nylon) (Crippa et al., 2019). In both cases, the process is only carried out for post-industrial feedstock rather than post-consumer materials.

Apart from a few other niche applications, chemical depolymerisation is commercially unproven for the types of plastic packaging waste produced by FMCG companies. PET glycolysis may be applicable to PET packaging in future, but it is not yet a reality.

### 4.5.2 Environment

Though only used for post-industrial PET fibres at present, PET glycolysis is the sole commercially feasible process

that is likely to be relevant for FMCG companies. Only two studies appear to provide useful modelled data (Meys et al., 2020; Shen et al., 2010) but, unfortunately, they are case-specific and contradict each other. In the unlikely event that FMCG companies adopt PET glycolysis for post-consumer PET in the near future, it is recommended that they consider carefully the full life cycle benefits of doing so in comparison to other mature technologies, such as mechanical recycling, for which process parameters are much more certain.

### 4.5.3 Health

The lack of process data makes it challenging to assess the health implications of PET glycolysis. In any case, it appears to be unsuitable for processing post-consumer packaging. Should near-future advances enable the use of this technology to process post-consumer materials from FMCG companies, efforts should be made to ensure that emissions of hazardous substances are controlled to prevent exposure to human and environmental receptors

## 4.6 Approach 6: Pyrolysis and gasification

### 4.6.1 Overview

#### Pyrolysis

Pyrolysis of plastics involves heating the material under moderate pressure without oxygen (Mayer et al., 2019). Unlike combustion, the polymers don't oxidise (Lopez et al., 2017) but break up randomly, fragmenting and reforming to resemble hydrocarbon molecules found in crude oil (Ragaert et al., 2017).<sup>15</sup> The liquid product (80 per cent by weight) is often distilled into three basic fractions – kerosene, diesel and light oils (naphtha) – whereas the solid fraction (20 per cent by weight), known as char, includes non-combustible minerals and metals, as well as a high proportion of black carbon (Butler et al., 2011).

The liquids from pyrolysis plants are all combustible, and according to Crippa et al. (2019), the most viable end-use for these is as fuel for ships and power plants. If sufficiently refined, pyrolysis oils can be used in higher grade applications, such as road vehicles or aviation (Lopez et al., 2017). However, the ambition of many

pyrolysis developers is to refine these oils into monomers and other compounds that can be used in primary plastic production.

The creation of plastic production feedstock has the potential to both reduce the need to extract further fossil fuels, and reduce the disposal and recovery burden on other parts of the waste management system (Hann and Connock, 2020). If the process was able to compete commercially with mechanical recycling, the value of waste plastics would increase; creating a disincentive to mismanage plastics. Though pyrolysis innovation has accelerated in recent years, there is little evidence that pyrolysis oils have been used to produce monomer feedstock (Solis and Silveira, 2020).

Solis and Silveira (2020) reported that several plastic waste pyrolysis plants exist, and indicated that 'conventional pyrolysis' is currently at TRL 9. However, their review also points out that there are few full-scale projects from which to determine economic feasibility, raising some doubt about how close these projects are to commercialisation.

<sup>14</sup> Glycolysis of polyester is the process whereby glycol diethylene glycol or propylene glycol molecules are inserted into the polyethylene terephthalate polymer chains, causing them to fragment and produce bis(2-hydroxyethyl) terephthalate (BHET) and a range of oligomers. The BHET can be used as a 'starting material' to make new PET/polyester.

<sup>15</sup> When plastics are combusted, the polymer chains break down into hydrocarbon fragments and atoms. If combustion is complete, these free molecules and atoms bond with oxygen to create water and carbon dioxide; this process is also called oxidation.

Khoo (2019) indicated that several plants exist, including one in Japan (processing 15,000 tonnes per annum) and two in the US (of which one processes 25,000 tonnes per annum; the other is expected to process 100,000 tonnes per annum once operational). At the time of writing, none of the plants reported by Khoo (2019) are verified as providing commercially proven processes.

Though there are undoubtedly facilities that can maintain a pyrolytic process, their independent economic viability is critical to the sustainability of the technology in the context of other mature and stable approaches, such as mechanical reprocessing. Until more data becomes available, the possibility that pyrolysis of waste plastics is unsustainable and undesirable should remain under consideration (Rollinson and Oladejo, 2019).

## Gasification

As with pyrolysis, gasification of plastic waste involves heating the material to break down the bonds between the hydrocarbon (polymer) chains. The key difference is that some oxygen is introduced, allowing partial oxidation of some of the fragments and atoms, but without allowing full combustion to take place. The result is the production of gases such as carbon monoxide (CO), hydrogen (H<sub>2</sub>), carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrogen (N<sub>2</sub>), alongside other hydrocarbons such as C<sub>2</sub>H<sub>4</sub> and C<sub>2</sub>H<sub>6</sub> (Ciuffi et al., 2020; Punkkinen et al., 2017). Gasification takes place at higher temperatures compared to pyrolysis, typically 700–1,200°C, which means plants tend to be much larger (Solis and Silveira, 2020).

Char is also produced during gasification and contains a mixture of tarry polycyclic aromatic and heterocyclic hydrocarbons (Wolfesberger et al., 2009). Removal of these complex molecules from the black carbon is unviable (Benedetti et al., 2017; Lopez et al., 2018) and they quickly condense in the process, corroding and clogging pipework (Zeng et al., 2020). While there is clearly potential for further use of pyrolytic chars from plastic waste, it seems likely that the barriers to upgrading will result in the material either being combusted or disposed of as hazardous waste (Defra, 2013). Due to the higher volatility of the feedstock, gasification of plastics produces less char compared to gasification of biomass or fibre (Sharuddin et al., 2016). The downside is that the char particulates do not condense, but remain in the syngas (Lopez et al., 2018; Solis and Silveira, 2020).<sup>16</sup>

There is little information to evidence the commercial viability of gasification plants that use waste plastics as a feedstock. Just three reviews have been carried out of plants that have existed over the last two decades, each of which indicate uncertainty about whether the plants they have reviewed are still operating (Jayarama Reddy, 2016; Seo et al., 2018; Solis and Silveira, 2020). Quicker (2019) indicated that gasification of homogenous mixed plastics

had been shown to be viable at a plant in Germany. However, he cautioned that the plant has suffered from technical difficulties over many years and questioned the overall viability of the process.

Theoretically, the syngas from waste gasification can be upgraded and used to produce a range of chemical substances, such as ammonia, methanol and hydrogen (Antonetti et al., 2017). This is typically the objective of coal gasification plants (Ciuffi et al., 2020). Crippa et al. (2019) also reported that gasification of coal in China has been used successfully to produce some plastics production precursors, such as ethylene glycol, but asserted that there is little evidence to support any polymer precursor production at commercial scale anywhere else, and certainly not from waste plastics.

Critics such as Rollinson and Oladejo (2020) have indicated that it is unlikely that any commercially viable upgrading of syngas from gasification plants processing waste plastics has taken place in recent years. Given the lack of affirmation in the literature reviewed here, this assertion seems reasonable. Even as a fuel, waste gasification becomes less viable due to the need to remove moisture from the syngas before it is combusted. Tentatively, it is suggested that syngas from gasification is, at best, converted into fuels, however it is more likely that they are combusted directly in the plant, thus operating as an efficient incinerator.

## 4.6.2 Environment

Pyrolysis and gasification are the most commercially mature group of chemical recycling technologies that can process waste plastics, yet there are still few examples of them being used for anything other than fuel production. Where they produce fuel, they appear to generate fewer emissions compared to incineration, but they generate more emissions than mechanical recycling (Khoo, 2019; Schwarz et al., 2021).

Some theoretical models have inferred that the processors would produce fewer emissions in comparison to mechanical recycling if starting material could be produced (Francis, 2016a; Francis, 2016b), although this does not appear to be a commercial reality at the time of writing (Crippa et al., 2019; Rollinson and Oladejo, 2020). The unique selling point (USP) for both pyrolysis and gasification is their versatility in processing wastes that are too complex or contaminated to undergo mechanical sorting and reprocessing, either because they are multi-layered or because they are technically and/or economically challenging to sort (Ragaert et al., 2017; Solis and Silveira, 2020). But there is evidence that they require nearly as much sorting where outputs are intended to be used as feedstock, and that this could increase the overall life cycle carbon emissions enough to nullify the potential benefits (Schwarz et al., 2021).

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<sup>16</sup> Syngas is mainly comprised of carbon monoxide (CO), hydrogen (H<sub>2</sub>), methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) gases in varying proportions according to the feedstock being gasified.





📍 Plastic recycling facility run by Tearfund’s partners Arris Desrosiers. Photo: Kit Powney/Tearfund

Both gasification and pyrolysis have experienced significant operational limitations, including tar removal and char disposal for the former (Benedetti et al., 2017; Lopez et al., 2018; Wolfesberger et al., 2009; Zeng et al., 2020), and high energy inputs for the latter (Crippa et al., 2019; Mayer et al., 2019; Ragaert et al., 2017; Sherwood, 2020). Regardless of any modelled emission reduction from using pyrolytic oils or syngas to produce starting materials, the control of fugitive emissions from the processes is critical.

It is not recommended that FMCG companies process their plastic packaging through pyrolysis or gasification in HICs or LMICs until the full life cycle impacts have been determined for these novel and immature technological approaches.

### 4.6.3 Health

Gasification and pyrolysis plants involve the use of equipment that operates under high heat and pressure, while also producing multiple hazardous substances that

can be fatal to humans and wildlife. Potential outputs from both gasification and pyrolysis are shown in [Table 3](#), though products of post-consumer plastic packaging waste transformation are unlikely to contain significant quantities of halide, dioxins and related compounds, metals or sulphur compounds.

With careful management, the emissions from gasification and pyrolysis can be captured, contained, disposed of, or transformed to prevent them from interaction with plants, animals and humans; guidance for doing this can be found in the ‘Best available techniques for incineration’ (Neuwahl et al., 2019). Moreover, as many of the substances can be burned, rendering them ‘safe’ through combustion is a tempting and often-practiced approach. However, process emission control can be costly and requires ongoing maintenance supported by effective safe systems of work. In countries that lack well-resourced, effective regulation and where corporate resources to manage safe systems may also be scarce, there is a risk of fugitive emissions and the mismanagement of hazardous residues.

Gasification projects tend to be much larger than pyrolysis, meaning that they are often better resourced. A serious emerging concern is the potential for small operators to set up pyrolysis operations without any kind of supervisory or regulatory oversight.

FMCG companies who are considering treating waste using either pyrolysis or gasification must consider how process emissions will be controlled by plant operators and ensure that solid, liquid and gaseous wastes are prevented from escaping into the environment. Where these products are unusable due to unresolvable contamination, it is recommended that FMCG companies adopt a duty of care towards their safe treatment or disposal. Importantly, sufficiently managed and regulated hazardous waste landfills or incineration facilities do not exist in many LMICs. If this is the case, then neither gasification nor pyrolysis should be considered.

Lastly, as much of the growth in pyrolysis has taken place in LMICs, plants may be constructed with limited safety considerations. Several life-threatening incidents of malfunction have been reported – both in LMICs and HICs – including: an explosion at a plant in Panchkula (India) in 2011 that resulted in several workers being injured; an explosion at a plant in Khanty-Mansiysk (Russia) in 2012 that resulted in eight deaths; an explosion at a plant in Budennovsk (Russia) in 2014; an accident in Chennai (India) in 2014 which killed one and left two others injured; an accident in Joensuu (Finland) in 2014 which injured three; and an accident in Furth (Germany) in 1998 that resulted in large amounts of toxic gases escaping and nearby residents being evacuated (International Power Ecology Company, 2014).

**Table 3:** Examples of emissions from gasification and pyrolysis of waste plastics (note that several products listed below are unlikely to occur as a result of plastic packaging transformation)

Phase	Pyrolysis	Gasification
Gas	Hydrogen; methane; ethane; ethene; propane, propene; butane; and butene (Williams and Williams, 1999)	Carbon monoxide; hydrogen; carbon dioxide; methane, nitrogen; ethylene; ethane; (Ciuffi et al., 2020; Punkkinen et al., 2017); hydrogen sulphide; carbonyl sulphide; ammonia; hydrogen cyanide; alkali metals; hydrogen chloride; potentially toxic elements (Block et al., 2019)
Liquid	Ethylbenzene; styrene; toluene; polycyclic aromatic hydrocarbons (Budsareechai et al., 2019; Miandad et al., 2019)	na
Solid	Black carbon; non-combustible minerals (Butler et al., 2011); potentially toxic elements; aliphatic hydrocarbons and aromatic hydrocarbons (Bernardo et al., 2012)	Black carbon; non-combustible minerals; heterocyclic hydrocarbons – pyridine and phenol; light aromatics – benzene and toluene; polycyclic aromatic hydrocarbons – naphthalene; heavier hydrocarbons – not often characterised (Wolfesberger et al., 2009)

## 4.7 Approach 7: Co-processing in cement kilns

### 4.7.1 Overview

Approximately 7 per cent (2.3 and 2.6 billion tonnes of CO<sub>2</sub>eq) of global carbon emissions come from cement production (Hertwich, 2020; Lehne and Preston, 2018), half of which come from the use of fossil fuels (mainly coal) to heat calcium carbonate to produce clinker (Kara, 2012). The identification and use of alternative fuels is therefore critical to meet climate change targets (Gerassimidou et

al., 2020). For instance, solid recovered fuel substituted 42 per cent of European cement production energy demand in 2015 (MPA Concrete Centre, 2017). Some evidence suggests that so-called ‘co-processing in cement kilns’ has been carried out with plastic waste that has been collected for recycling (Jiao, 2020; Republic Cement, 2020), though there is little data to evidence the global prevalence of this practice.

## 4.7.2 Environment

The majority of LCA evidence for co-processing of alternative fuels in cement kilns is related to non-plastics or plastics mixed with other (often biogenic) materials (Bourtsalas et al., 2018; Georgiopoulou and Lyberatos, 2018; GIZ-LafargeHolcim, 2020; Khan et al., 2020; Malijonyte et al., 2016; Séverin et al., 2010; Vermeulen et al., 2009). These studies tend to favour co-processing of alternative fuels in cement kilns above incineration due to the displacement of coal, for which almost any other fuel source will show reduced carbon emissions.<sup>17</sup> Though the biogenic content of solid recovered fuel is likely to be a factor, four studies were identified that investigated the use of plastic packaging alone (Jenseit et al., 2003; Meys et al., 2020; Schmidt et al., 2009; Shonfield, 2008). In summary, they show broadly similar hierarchy of life cycle benefits, with greater emissions compared to mechanical recycling and fewer compared to incineration with energy recovery; findings commensurate with those reported by Lazarevic et al. (2010). Though the evidence is scant, it is hard to see how co-firing cement kilns with post-consumer plastic packaging waste would provide notably less environmental impact compared to incineration with energy recovery.

## 4.7.3 Health

Combustion of solid recovered fuel is likely to result in the production of several hazardous substances that

must be controlled to protect human health and the environment. The majority of studies to evidence these emissions are related to mixed feedstocks (Conesa et al., 2011; Rovira et al., 2010; Rovira et al., 2016) and particularly chlorine (Gerassimidou et al., 2020), which can form dioxins and furans as well as hydrochloric acid that damages equipment. But plastic packaging is unlikely to contain chlorine, and although not strongly evidenced, the emissions from plastic packaging combustion are unlikely to be much worse than the coal which it has replaced and almost certainly better than mixed solid recovered fuel which is likely to have a higher ash and moisture content (Asamany et al., 2017).

As with all of the approaches reviewed in this report, emissions from co-processing in cement kilns are technically possible to control through 'best available techniques' (Schorcht et al., 2013). As most cement production is carried out by well-resourced multinational corporations, implementing these techniques should be feasible. Speculatively, facilities that are less stringently regulated in some LMICs may be at risk of lack of emissions control, though there is no evidence to support this. Nonetheless, where resources are insufficient to guarantee safe operation, FMCG companies should consider independent auditing to ensure emissions meet at least European (European Union, 2000) or Chinese emission thresholds (Cheng and Hu, 2010; Wu, 2018).

# 4.8 Approach 8: Incineration with energy recovery

## 4.8.1 Overview

Waste incineration effectively reduces the mass (75 per cent by weight) (Dalager and Reimann, 2011) and volume (90 per cent volume per volume) (Hjelmar et al., 2011) of municipal solid waste. When used to treat the whole

fraction of municipal solid waste, incineration also reduces its bioactivity (Niessen, 2010), the critical characteristic that makes municipal solid waste so damaging when it is landfilled. Incineration has been rapidly adopted in Europe, China, Japan and Korea, and proportionally less so in the US ([Table 4](#)).

<sup>17</sup> Coal extraction releases fugitive emissions of methane, a small but non-negligible source of emissions from the life-cycle of coal used in combustion; reported as 1.91–4.23 grams of CH<sub>4</sub> per kilogram of coal (ar) for over and underground mined coal respectively (Spath et al., 1999).

**Table 4:** Number of municipal solid waste incinerators in selected countries and regions

Region / country	Number of plants	Reference
Europe	>500	Blasenbauer et al. (2020)
US	75	United States Environmental Protection Agency (2019)
Japan	1,200 <sup>18</sup> (778)	Amemiya (2018)
Korea	172 (35)	Bourtsalas et al. (2019)
China	390	Ministry of Housing and Urban–Rural Development (MoHURD) (2019)
India	5 <sup>19</sup>	Kumar and Agrawal (2020)
Azerbaijan	1	The World Bank (2013)
Ethiopia	1	Mutethya (2020)

In LMICs, efforts to introduce incineration have been less successful. Modern incinerators are comparatively expensive to construct and operate. Emissions abatement and plant efficiency rely heavily on suitable feedstock characteristics (Ji et al., 2016) and the availability of engineering expertise and components, all of which have presented historical challenges and resulted in plant failures in LMICs. For instance, Nixon et al. (2017) reported that most waste-to-energy incineration projects in India have failed either before or after commissioning, detailing examples of unsuccessful projects in Hyderabad, Vijayawada, Chandigarh and New Delhi.

In Ethiopia, a facility was recently constructed by a European–Chinese consortium in response to a chronic waste disposal problem in Addis Ababa, which resulted in the collapse of an unstable waste pile at a local dumpsite in 2017, killing 113 people (Law and Ross, 2019). The plant was shut down in 2019 shortly after opening, prompting fears of another failed LMIC waste-to-energy project. However, at the time of writing, at least one news report (Mutethya, 2020) has indicated that the facility has reopened and that commissioning will continue until the eventual handover to local employees in 2021. The longevity of this project beyond the commissioning phase will be closely watched in the context of reported failures elsewhere, and at least one similar project in sub-Saharan Africa has been reported to be underway

in Kenya (Najimesi, 2019). There appears to be demand for incineration of waste elsewhere according to Kadir et al. (2013), who reported that installation of large-scale incineration in Malaysia is ‘inevitable’ given government aspirations to develop the country’s infrastructure.

#### 4.8.2 Environment

While incineration is usually used to treat whole fraction of municipal solid waste, it is rarely used to treat plastics collected for recycling (Christensen et al., 2011a; Christensen et al., 2011b; Hjelmar et al., 2011). Though there is an inferred benefit to incinerating plastics compared to mechanical recycling in some studies, it usually performs worse in most LCAs (Lazarevic et al., 2010). Incineration of mixed waste with energy recovery generally shows an emissions reduction in comparison to electricity generation from fossil fuels (Laurent et al., 2014), because the latter emit methane during the extraction phase (Spath et al., 1999; Turconi et al., 2013). As decarbonisation of energy supplies progresses, the case for incinerating post-consumer plastic waste to make energy will diminish further. A further concern is that heat may not be recovered from incinerators in LMICs. There is no information provided here, but this should be considered in any future assessment of life cycle emissions.

<sup>18</sup> It is unclear whether all of these facilities process municipal solid waste.

<sup>19</sup> There is indication that some of these may not be fully operational or are in commissioning (Best Current Affairs Center, nd). Numbers in brackets represent facilities reported to include energy recovery.



❏ Kalamu River in Kalamu commune. Turning plastic waste into an economic opportunity – Kinshasa, DRC – Tearfund is co-implementing the project with the Church of Christ in Congo (ECC – Eglise du Christ au Congo). Photo: Flot Mundala/Tearfund

In general, there doesn't seem to be much environmental benefit to incinerating post-consumer plastic packaging waste that has been separately collected for recycling, beyond some possible unique situations. Given that mechanical recycling exists almost everywhere and, if it doesn't, material can easily be exported to somewhere where it exists, it is hard to justify why separately-collected plastic packaging waste would be incinerated for energy recovery.

### 4.8.3 Health

Historically, waste incinerators have had a poor reputation for environmental pollution and health due to significant emissions of hazardous substances (Herbert, 2007; United States Environmental Protection Agency, 2019; Walsh, 2002). Since the late 1990s and early 21st century, emissions cleaning technology has improved considerably, so that the majority of emissions to the atmosphere can be controlled by managing the rate and intensity of combustion and capturing hazardous substances with air pollution control equipment.

The risk of harm from hazardous substances emitted by well-managed European municipal solid waste incineration is likely to be minimal (Ashworth et al., 2014; Douglas et al., 2017; Freni-Sterrantino et al., 2019; Ghosh et al., 2019; Parkes et al., 2020). However, there is a legitimate concern about whether similar standards would be applied in LMICs, where the capacity for regulation and enforcement may not be sufficient to ensure emissions are kept within safe levels. China is rapidly developing capacity for municipal solid waste incineration and has implemented near-commensurate standards in comparison to Europe and the US (Cheng and Hu, 2010; European Union, 2000; Ji et al., 2016; Wu, 2018).

Incineration with energy recovery is not recycling, and FMCG companies should avoid incinerating post-consumer plastic packaging that has been collected for recycling.

# 5 Discussion

## 5.1 Commercial maturity and data availability

Based on the assessment in [Sections 4.1–4.8](#), the indicated maturity of each approach is ranked in [Table 5](#). An additional entry is provided for pyrolysis and gasification to differentiate the level of maturity for process outputs that are used for fuel or feedstock.

The three so-called ‘chemical recycling’ technologies (solvent-based purification, gasification and pyrolysis, and chemical depolymerisation) have barely been implemented for processing plastic packaging. Pyrolysis and gasification are the closest to commercialisation, but this review finds no robust evidence to suggest that they will reach commercial maturity. Several authors have indicated that they may never become commercially viable for post-consumer plastic packaging, as the output products can be more cost-effectively produced using other feedstocks and/or processes (Hann and Connock, 2020; Rollinson and Oladejo, 2020). As indicated by Rollinson and Oladejo (2020), these processes could turn out to be a ‘white elephant’, at least in the near future, creating a distraction from more urgent concerns to recover value from waste. Importantly, none of these technologies seem to fulfil the aspiration of being able to process mixed plastic waste and thus negate the high sorting and selective collection costs that can damage the business case for recycling plastics.

Though cement kiln incineration has become more common in the last decade, most of the process data are for mixed solid recovered fuel which includes biogenic material. This makes it challenging to assess the environmental performance of plastic packaging waste when used as a substitute for fossil fuels. However, because plastics are fossil fuels, it is unlikely that they will show much benefit in comparison to a biogenic–fossil mixture. Moreover, as energy generation decarbonises, the amount of any combustion of plastics is likely to diminish as the comparators are no longer fossil-based.

Though brick and tile production technology also lacks maturity, it is very basic and therefore the life cycle benefits can be assumed to an extent. The high burdens from concrete and ceramic production, which mineral-

polymer composite tiles and bricks would replace, are likely to be considerable. However, the black carbon produced on the open wood fires used to heat the sand and plastic should also be accounted for in any future life cycle assessment. Importantly, the technology tends to be implemented at a much smaller scale, to solve localised issues of environmental debris, an indicator that is not considered in life cycle assessments.

**Table 5:** Indicative maturity of each of the eight approaches reviewed

Approach		Maturity
1	Conventional mechanical reprocessing for extrusion	High
2	Bottle-to-fibre mechanical reprocessing for extrusion	High
7	Co-processing in cement kilns	High
8	Incineration with energy recovery	High
3a	Mineral–polymer composites: road surfacing	Medium to high
3b	Mineral–polymer composites: brick and tile production	Medium to high
6	Pyrolysis and gasification for fuel	Medium to high
4	Solvent-based purification	Low
5	Chemical depolymerisation (chemolysis)	Low
6	Pyrolysis and gasification for feedstock	Low

## 5.2 Environmental impact

### 5.2.1 Carbon emissions

This review finds that the life cycle carbon emissions of the eight approaches reviewed infer a ranking that is commensurate with the Waste Hierarchy. Mechanical recycling, including bottle-to-fibre technology, results in the least emissions (as demonstrated by many studies), and incineration with energy recovery results in the most. As discussed in [Section 5.1](#), cement kiln incineration lacks specific data for plastic packaging, but indicatively it appears on a par with incineration if not slightly better. However, at least two authors highlighted the influence of sorting and washing on the mechanical recycling process, which may weaken the life cycle case in favour of incineration by cement kiln or otherwise. The case for the use of plastics in roads, bricks and tiles is less clear and there is no robust data at all to indicate the amount of carbon displaced by their use. However, the fact that they are a waste that replaces fossil fuels and/or minerals indicates that they are likely to reduce primary material extraction and production burdens.

The lack of published lifecycle emission data for all chemical recycling technologies makes it challenging to put them in context. A theoretical model is provided by Schwarz et al. (2021) which shows relative CO<sub>2</sub> emissions from processing 25 different polymers. The study shows broad agreement with the findings of this report, indicating that mechanical recycling results in the fewest emissions. When they result in monomer production, both gasification and pyrolysis result in broadly similar if not slightly fewer emissions – though these processes are yet to be utilised in this way, as there are no commercially active plants in operation and therefore such findings need to be treated with caution.

## 5.3 Health

It is possible to control emissions from most industrial processes given sufficient engineering controls and management. However, in LMICs, the lack of resources and know-how mean that high-tech engineering approaches may not be sufficient to do so. All thermal processes involving plastics may heighten the risk that harmful substances are released and emitted into the surrounding environment. Even in low-risk packaging plastics extrusion plants, if the provenance of extruded material is not controlled to ensure contamination cannot

The limitations of LCA studies were discussed in this review, particularly the poor handling of data by practitioners and failure to acknowledge material losses in the process. As highlighted by Geyer et al. (2016), the key metric is not the mass of material that is collected for recycling, nor the amount that is actually reprocessed and converted into new products. Life cycle benefits should be based on the mass of material displaced and subsequent avoided burdens. Doing this may favour applications such as road surfacing, tile-making and bottle-to-fibre polyester production.

### 5.2.2 Management of residues and pellet loss

The potential for mismanagement of sorting and reprocessing residues in LMICs is significant. In many countries where mismanagement is already high, the authorities are unlikely to have the capacity to comprehensively oversee and enforce transgressions by commercial operators. Mismanagement includes open-burning, open-dumping and disposal into the aquatic environment. Moreover, in plants that comminute material or produce pellets, the probability of loss to drainage systems is considerable if not managed adequately. Though this review focuses on debris emissions from mechanical reprocessors, all of the approaches reviewed here have the potential to result in mismanagement of residues.

take place, there is a risk that materials from, for instance, electrical or automotive use could be co-extruded, risking exposure of substances such as brominated flame retardants to workers or nearby residents.

# 6 Conclusion and recommendations

Post-consumer plastic packaging waste that has been collected for recycling should be processed in safe facilities. These plants should use approaches that are mature enough to guarantee minimal emission of potentially hazardous substances and materials to the environment, and which ensure that public and occupational health are protected.

All of the approaches reviewed here have the potential to cause harm to the environment, public and occupational health. However, with sufficient process emission control, and safe systems of work, they can be operated safely. This report finds no evidence to fundamentally oppose the use of any of them in the right context. However, self-management of risks cannot be guaranteed anywhere, in high-, middle- or low-income countries. Comprehensive public and environmental health protection requires effective, well-resourced and independent regulation, which may not be available in countries where competing priorities limit resource availability to fund them.

Most of the large FMCG companies have begun to pursue targets to reduce their resource use, use more recycled materials in plastic packaging, and implement systems to recycle the large amounts of post-consumer plastic packaging waste that they place on the market. This report aimed to assist stakeholders with decision-making; to encourage the choice of technological approaches that cause the least harm to human health and the environment.

In [Figure 3](#), the eight approaches reviewed have been qualitatively assessed using a red, amber, yellow, green indicator system for their potential impact on health and the environment in high-, middle- and low-income contexts, and their level of technological maturity. In addition, the risk of operating below standards in LMICs is shown as an ‘appropriateness’ score. Three main groups of approaches ([Groups 1–3](#)) are evident from the assessment, the first of which is subdivided into two further sub-groups ([Groups 1a](#) and [1b](#)).

## Group 1a

There is strong evidence to suggest that the approaches in [Group 1a](#) are the least impactful on the environment, and although they carry some environmental and health risks, they have the greatest potential to be operated within standards ([Figure 3](#)). Plastic packaging that has been collected for recycling should be processed by mechanical reprocessors where feasible, available or implementable as this is the most mature technology with the lowest evidenced life cycle emissions. Bottle-to-fibre is probably

just as beneficial as mechanical reprocessing and the inferred benefits of closed- over open-loop systems is not supported by strong evidence; though acknowledging that this may change over time when increased material cycles become a reality.

## Group 1b

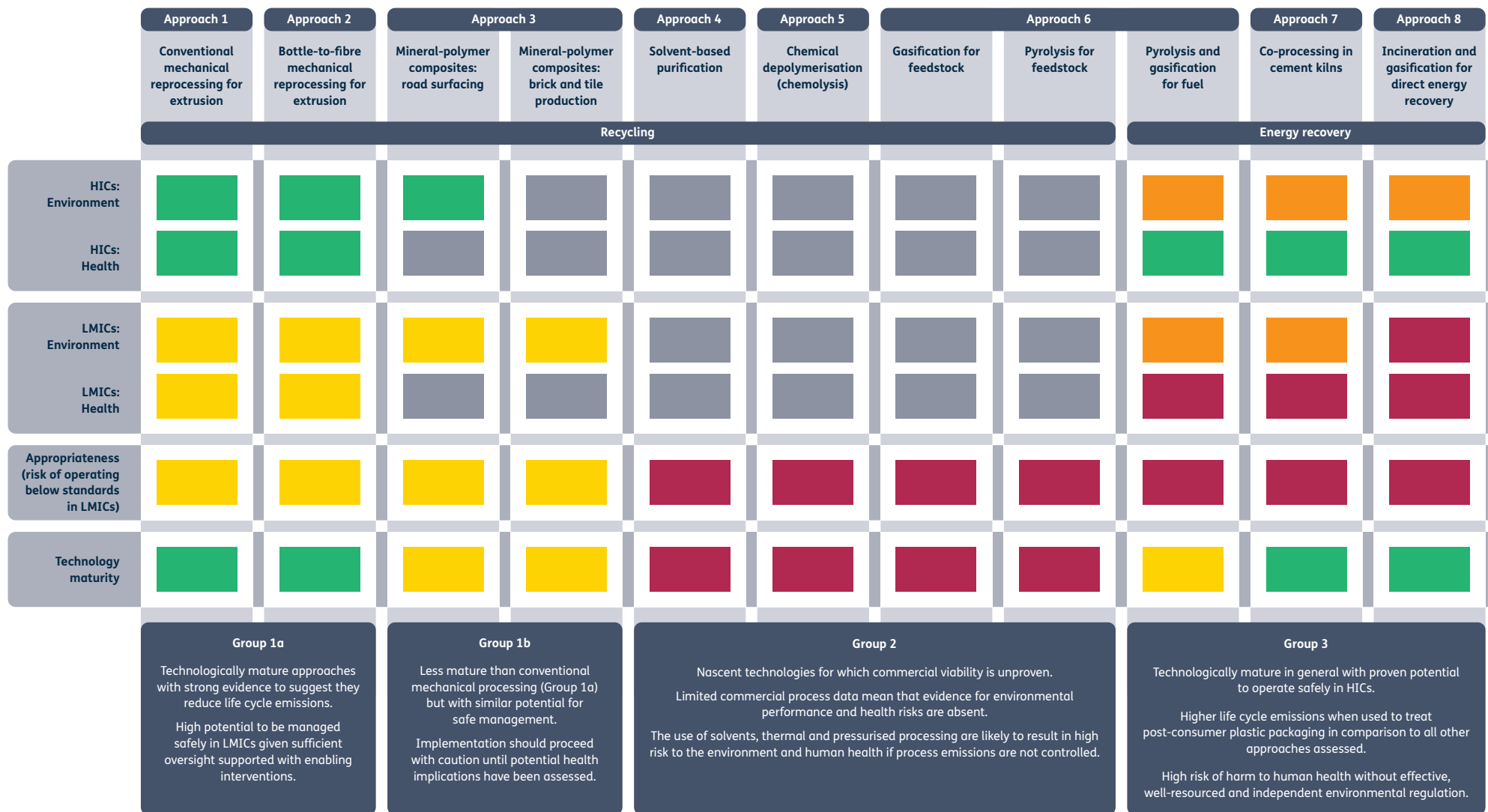
It is possible that the approaches in [Group 1b](#) (road surfacing, brick and tile production) have a similar level of risk to [Group 1a](#), however there is relatively little data available to assess them ([Figure 3](#)). It is recommended that these processes are adopted cautiously until process emissions from melting have been determined and therefore the potential for occupational hazard exposure can be reliably assessed. It is recommended that FMCG companies who aim to reduce carbon emissions and want to explore technologies other than mechanical recycling commission ISO:14040 LCA studies to determine these emissions.

## Group 2

The chemical recycling approaches in [Group 2](#) are nascent and their commercial viability is unproven ([Figure 3](#)). This review finds no objection to investigating these technologies further, but cautions that they should not be considered for commercial processing of post-consumer plastic packaging waste until their environmental benefits have been demonstrated. Where FMCG companies are considering adopting any of these novel processes, is recommended that they adopt or initiate an independent auditing body that can certify the processes for safety and efficacy, as recommended by Crippa et al. (2019), to ensure that any approach results in no harm to human health and the environment and provides clear life cycle benefits.

All of the processes in the group may involve the use of heat, pressure and chemical solvents, each of which are likely to result in environmental or health impacts if not carefully controlled. Tars and chars from pyrolysis and gasification can contain highly hazardous substances that must be disposed of in hazardous landfills or through thermal processing. To ensure that any approach to processing packaging does not result in harm to health or the environment, it is recommended that FMCG companies adopt a full duty of care towards these materials and substances if generated in LMICs. It may not be possible to ensure that hazardous waste is managed responsibly in these countries, and this might mean that some processes cannot be carried out safely at all.

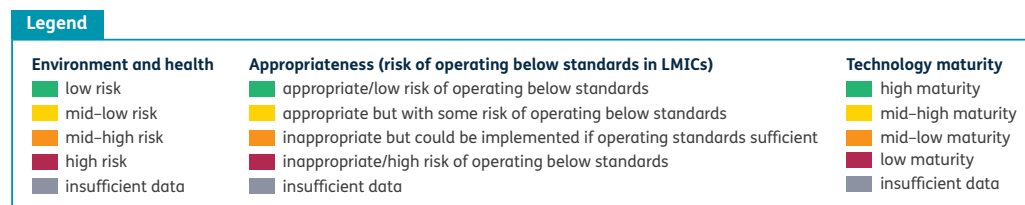




**Figure 3:** Summary of indicative environmental and health risks, and appropriateness for implementation in LMICs, for approaches to processing post-consumer plastic packaging waste generated by fast-moving consumer goods companies

**Abbreviations**

HICs - high-income countries  
LMICs - low- and middle-income countries



Anecdotally, there appears to be an increasing number of small-scale pyrolysis facilities in LMICs in recent years. Given the high risks of these technologies being operated below standards, FMCG companies should avoid the use of these plants for processing their post-consumer plastic packaging waste.

### Group 3

Though mature and capable of being safely operated, incineration of post-consumer plastic packaging with energy recovery is not recycling and results in higher emissions compared to all other approaches because plastic is a fossil fuel (Figure 3). It is likely that cement kiln co-processing results in marginally less emissions because it almost always displaces coal. However, the gains are so marginal that it is hard to justify why it would be prioritised ahead of mechanical recycling. Pyrolysis for fuel or direct combustion is a less mature technology, but is also theoretically operable at a high level of safety. However, limited evidence suggests that greenhouse gas emissions are still likely to be much higher than mechanical recycling, as the feedstock is fossil carbon. When used to process plastic packaging waste, cement kiln co-processing, incineration with energy recovery, and pyrolysis-to-fuel technologies will show decreasing benefits as energy supplies decarbonise over the coming decades.

The case for incinerating plastic packaging that is not practically recyclable or that has high levels of surface contamination may offer a slight improvement where mechanical recycling is the comparator, because of the high burdens associated with hot-washing in mechanical recycling. However, designing packaging for recycling and collecting it separately to avoid contamination is likely to result in overall reduced environmental and health burdens.

### Assurance

If the aspiration of FMCG companies is to protect human health and the environment, it is recommended that they ensure post-consumer plastic packaging collected for recycling is processed in facilities which meet standards that ensure they achieve that objective. If European ‘best available techniques’ are followed, these objectives can be achieved. For high-risk approaches such as those in Groups 2 and 3, a prerequisite for safe operation is to have an environmental regulator that is independent, well-resourced, and which has sufficient powers of enforcement to ensure compliance. Where this is not possible, other independent auditing and monitoring bodies could replace that function. Of course, independent auditing is not without potential shortcomings. As described by Cook et al. (2016), professional auditors are also subject to issues of neutrality, objectivity and transparency. In any case, given the high cost of sufficient emission control and safe operation, it is likely that the business case would not support using these processes in LMICs.

Best available techniques are not available for the lower risk activities in Group 1. Though Basel Convention (nd) provides some high-level recommendations for environmentally sound management, these are nearly two decades old and require updating. Some basic operational risks have been described in this report, but it is recommended that FMCG companies commission a project to develop evidenced standards that can be used to compliment the growing mass of material which they intend to process over the coming decades. Within these standards, a clear pathway to enable compliance from small-scale and grassroots reproducers should ensure that the waste processing landscape is accessible to a wide range of actors along the value chain and does not become exclusive to large-scale, well-resourced entities.

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# Appendix: Detailed Approach

## A1 Scope, definitions and report structure

This report focuses on ‘single-use’ plastic packaging that has been placed on the market by FMCG companies and subsequently ‘collected for recycling’ after it has become waste. It excludes approaches that involve processing plastic packaging waste that is mixed with other materials. In [Section 2](#), a short assessment of what constitutes safety is presented which includes a discussion on some of the methods of assessing safety such as life cycle assessment ([Section 3.2](#)).

Discussions between Tearfund and FMCG companies identified eight general approaches that are being considered or actively pursued by FMCG companies as solutions to recovering value from plastic packaging ([Table 6](#)).

Each ‘approach’ section is divided into three subsections as detailed in [Table 7](#).

**Table 6:** Approaches to recovering value from post-consumer plastic packaging waste that has been collected for recycling

<b>Approach 1</b>	Conventional mechanical reprocessing for extrusion	<a href="#">Section 4.1</a>
<b>Approach 2</b>	Bottle-to-fibre mechanical reprocessing for extrusion	<a href="#">Section 4.2</a>
<b>Approach 3</b>	Mineral-polymer composites: Road surfacing; brick and tile production	<a href="#">Section 4.3</a>
<b>Approach 4</b>	Solvent-based purification	<a href="#">Section 4.4</a>
<b>Approach 5</b>	Chemical depolymerisation (chemolysis)	<a href="#">Section 4.5</a>
<b>Approach 6</b>	Pyrolysis and gasification	<a href="#">Section 4.6</a>
<b>Approach 7</b>	Co-processing in cement kilns	<a href="#">Section 4.7</a>
<b>Approach 8</b>	Incineration with energy recovery	<a href="#">Section 4.8</a>

**Table 7:** Structure of report sections that discuss approaches and core research questions

Subsection	Research questions
Overview	<ul style="list-style-type: none"> <li>• How much material is treated by this approach?</li> <li>• What is the technological maturity?</li> </ul>
Environment	<ul style="list-style-type: none"> <li>• What are the climate change impacts or avoided burdens?</li> <li>• Does this process have any impacts on biological populations, assemblages or ecosystems?</li> <li>• What would improve the environmental performance?</li> </ul>
Health	<ul style="list-style-type: none"> <li>• What are the potential impacts on the health, safety and welfare of workers engaged in the activity?</li> <li>• What are the potential effects of the process or activity on public health?</li> <li>• What would make this approach safe?<sup>20</sup></li> </ul>

<sup>20</sup> Answers may incorporate references to best available techniques (BATs), legal frameworks that can be borrowed to achieve minimum safety standards and indications for how FMCG companies can demonstrate that the process represents a safe end use.

## A2 Literature review

It was beyond the resources of this study to conduct a full, scientific, systematic review. Instead, this study has used existing reviews of evidence, supplemented by citation and snowball searching (Cooper et al., 2018) to identify more recent and other relevant work using Scopus, Google Scholar and Google search engines. Drawing on evidence from reviews introduces potential bias to the study, relying on the robustness of a third party's investigation. To address this with limited resources, samples of reviewed articles were checked to ensure that the findings of original works had been correctly and fairly represented. If there was an indication that this was not the case, further samples were taken and, if necessary, the third-party

review was rejected for inclusion. Other considerations included the number of times a review had been cited by others in the context of the publication date, the impact factor of the journal being published, potential bias of the authors or funders (particularly, but not exclusively, for non-peer reviewed work) and quality and thoroughness of interpretation by the author.

In some cases, no relevant reviews exist (for instance for co-processing in cement kilns), therefore individual papers were assessed that were relevant. It should be reiterated that this was not a systematic process and therefore there may be sources of information that have been overlooked.

## A3 Inclusion/exclusion criteria

Literature and other sources of information identified were assessed for inclusion in this study according to the criteria listed in [Table 8](#).

**Table 8:** Inclusion and exclusion criteria

Inclusion	Exclusion
<ul style="list-style-type: none"> <li>Conventional plastics</li> <li>Technologies listed</li> <li>Supply systems</li> <li>Post-consumer plastic waste</li> <li>Packaging</li> <li>Peer reviewed journal articles, conference papers, books, Reports, websites, online multi-media</li> </ul>	<ul style="list-style-type: none"> <li>Waste collection – eg waste pickers</li> <li>Biodegradable plastics</li> <li>International trade in plastic scrap</li> <li>Post-industrial waste</li> <li>Non-packaging</li> <li>Reuse/alternative delivery systems</li> <li>Film footage intended to expose poor practice</li> </ul>

In places, objective reasoning is applied by the author where the evidence is insufficient, though this is clearly stated in each case. Nonetheless, the report has attempted to be explicit about where the gaps in information lie and to avoid making judgements or extrapolations where the evidence is unavailable.

Assessment of life cycle benefits and impacts of plastic packaging during the use phase will also be excluded here, though it is strongly recommended that FMCG companies take a whole system approach to assessing the impacts of their products as described in [Section 3.1](#).

If we are to begin to manage resources more effectively and safely in an increasingly complex world, then decisions on which materials and substances to include in packaging, or how to treat that packaging when it is discarded, are not taken in isolation. For instance, packaging designers should consider the context in which their products are being used and managed, assessing the risk of mismanagement, and considering what waste treatment and reprocessing options are available. It is not sufficient for FMCG companies to place plastic packaging on the market in countries which do not have the capacity or capability to manage them safely when they become waste.

Each of these sections is divided into three subsections, as shown in [Table 7](#), which lists the core research questions. Finally, in [Sections 5](#) and [6](#), the various technologies and approaches are compared and summarised to assist with decision-making about which can be considered least impactful on health and the environment.

## A4 Visual assessment of online media

Although the focus of this review is on low-income countries, process information for the technologies being reviewed there is scant. To provide some insight, a review of multi-media (video) sources was carried out to identify potential safety implications of several processes that are not otherwise well reported. These were mechanical recycling and mineral-polymer composite slab and tile production.

Basic search terms were used to search YouTube to identify film footage of these activities, such as 'plastic and sand tile production' and 'plastic recycling'. In some cases, specific national terms were included such as 'India', 'China' and 'Brazil'. The objective of these searches was to assess either good or poor practice to benchmark potential extremes of behaviour, rather than assess the magnitude or prevalence of particular practices, as this would not be a robust method of doing so. Footage intended to expose poor practice was excluded to control the risk of bias and cherry-picking by film producers. Instead, the focus was on identifying footage that was intended to demonstrate a process, or 'showcase' an existing commercial operation.

As well as recording basic information about each process, a visual assessment of hazards was made which were grouped as follows:

1. Unguarded fast or high-torque machinery in close proximity to workers
2. Worker interaction with machinery resulting in risk of being drawn in
3. High temperature equipment in close proximity to workers, risking burns
4. Risk of interaction with unknown, potentially hazardous materials or substances (ie through atmosphere, dermal contact or ingestion)
5. Risk of burns from caustic substances
6. Particle loss to the environment likely
7. Risk of aerosolised hazardous substances
8. Risk of ballistic injury to hands, feet, body from interaction with sharp or heavy objects

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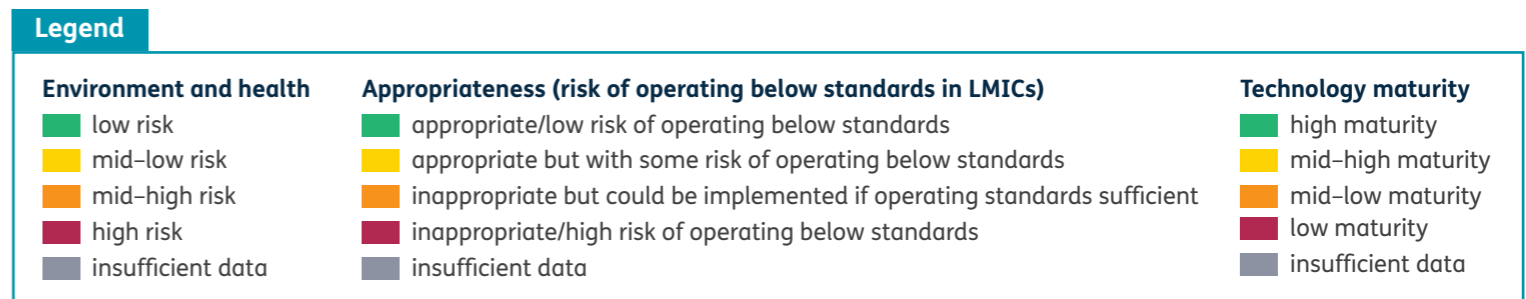
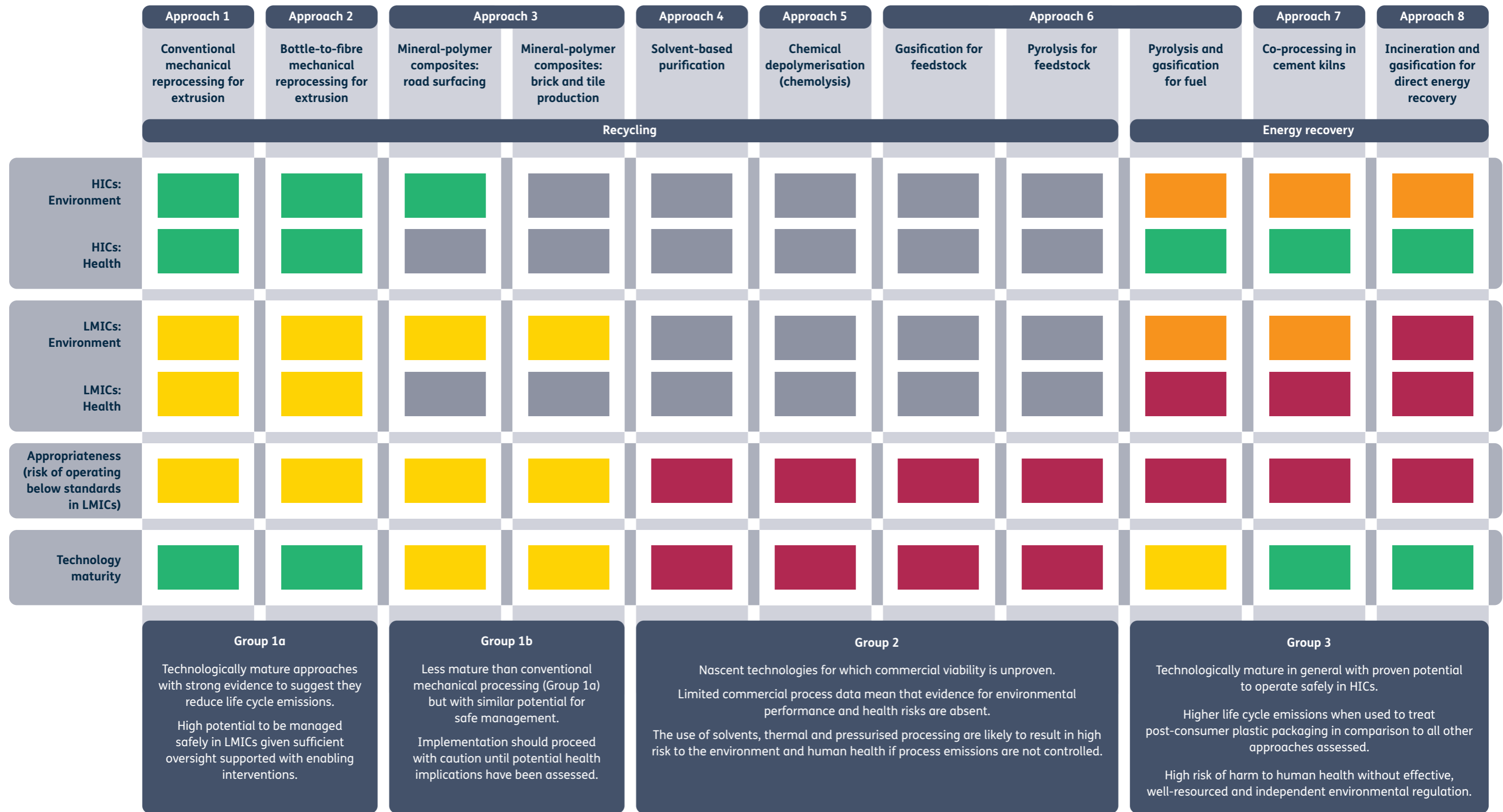
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**Abbreviations**  
HICs - high-income countries  
LMICs - low- and middle-income countries