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)

tearfund

Acknowledgements

Author

Ed Cook is a researcher with more than 20 years' experience in the waste and resources management sector. In the UK, he has worked as a business manager and waste management consultant, and globally, on emergency response and development projects in Mexico and Pakistan. Ed has co-authored several publications on the topic of waste plastics including:

- *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).

Ed currently works as a Research Fellow in Circular Economy Systems for Waste Plastics at the University of Leeds, though this report was conducted independently and is not endorsed by the institution. Ed is a Chartered Waste Manager with the Chartered Institute of Waste Management in the UK.

Reviewers

The author would like to extend his extreme gratitude to the following waste management sector professionals who provided extensive peer review and constructive criticism for an earlier version of this report.

- Professor David C Wilson (Independent consultant)
- Professor Linda Godfrey (Council for Scientific and Industrial Research – CSIR)
- David Lerpiniere (Resource Futures)
- Joanne Green (Tearfund)
- Mari Williams (Tearfund)
- Richard Gower (Tearfund)

Special thanks

The author is grateful to all of those who have offered their time to provide advice, experience and expertise that has helped with the production of this report. In particular he would like to acknowledge the following:

- Alexander Kumi-Larbi Jnr. (Imperial College London)
- Zoë Lenkiewicz (WasteAid)
- Sarah Edmondson
- Carla Valle-Klann (UN Environment)
- Dr Costas Velis (University of Leeds)
- Dr Josh Cottom (University of Leeds)

This report is the result of an independent academic review commissioned by Tearfund and funded by the Norwegian Agency for Development Cooperation (NORAD) and Tearfund. The findings and recommendations do not necessarily constitute Tearfund or NORAD policy.

Suggested citation

Cook, E. (2021). *Safety first: Recovering value from plastic waste in low- and middle-income countries.* Teddington, UK: Tearfund. **www.tearfund.org/safety-first**

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

Author: Ed Cook
Project lead: Joanne Green
Design: **www.wingfinger.co.uk**
Cover photo: Hazel Thompson/Tearfund

We welcome feedback on our publications and would be delighted to hear how you have used this resource. Please get in touch using the contact details below.

Published by Tearfund. A company limited by guarantee.
Registered Charity No 265464 (England and Wales)
Registered Charity No SC037624 (Scotland)

Tearfund is a Christian charity determined to see an end to extreme poverty and injustice. We mobilise communities and churches worldwide to help ensure that everyone has the opportunity to fulfil their God-given potential.

Tearfund, 100 Church Road, Teddington, TW11 8QE, UK

Tel: +44 (0)20 3906 3906
Email: publications@tearfund.org
Web: **learn.tearfund.org**

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

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

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

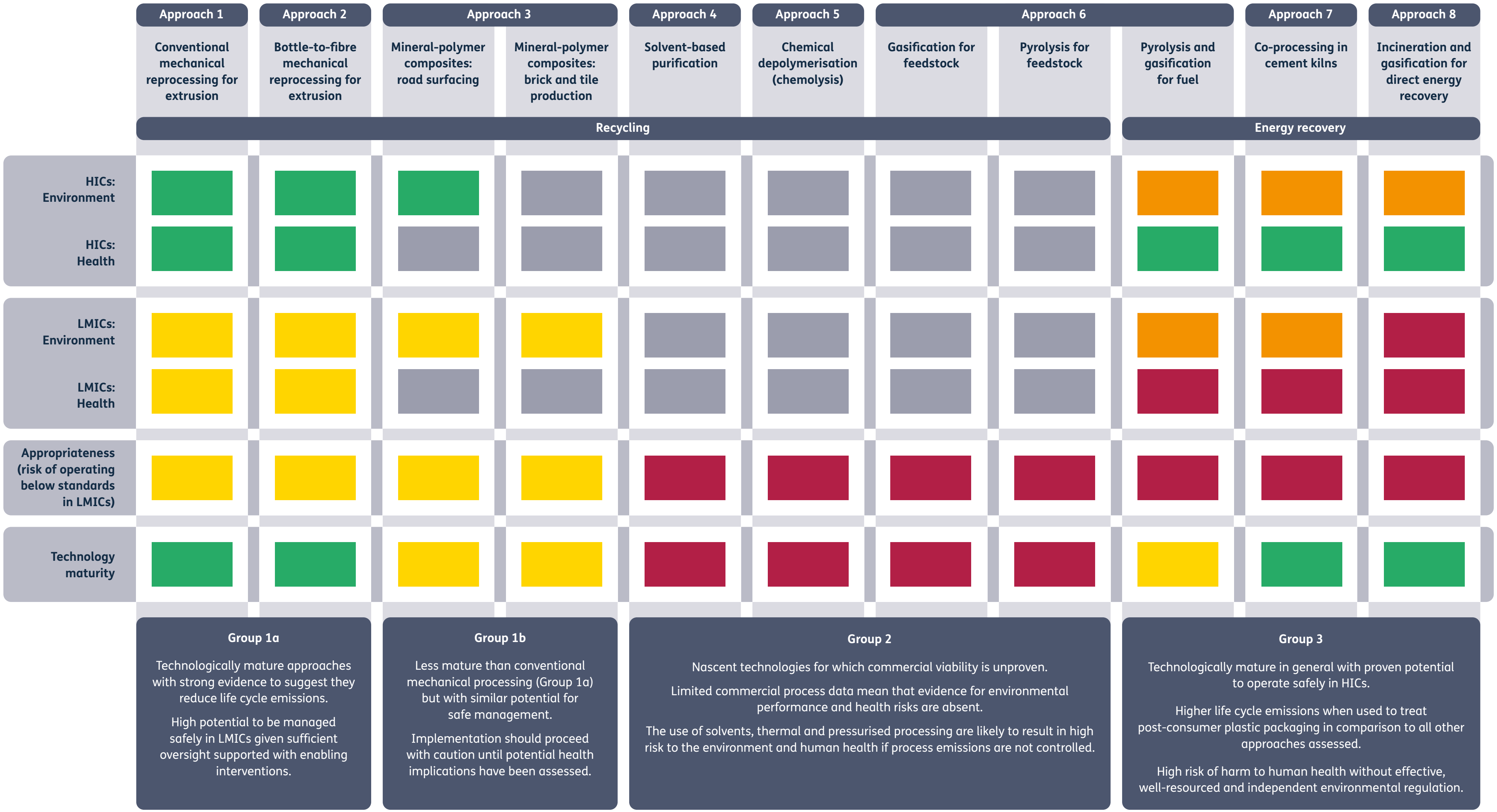


Figure 1: Summary of indicative environmental and health risks, and appropriateness for implementation in LMICs, for approaches to processing post-consumer plastic packaging waste generated by fast-moving consumer goods companies

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

Legend

Environment and health
- low risk
- mid–low risk
- mid–high risk
- high risk
- insufficient data

Appropriateness (risk of operating below standards in LMICs)
- appropriate/low risk of operating below standards
- appropriate but with some risk of operating below standards
- inappropriate but could be implemented if operating standards sufficient
- inappropriate/high risk of operating below standards
- insufficient data

Technology maturity
- high maturity
- mid–high maturity
- mid–low maturity
- low maturity
- insufficient data

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).

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.

Abbreviations

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

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.[1] 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

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

1 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.[2] 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'.[3] 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).

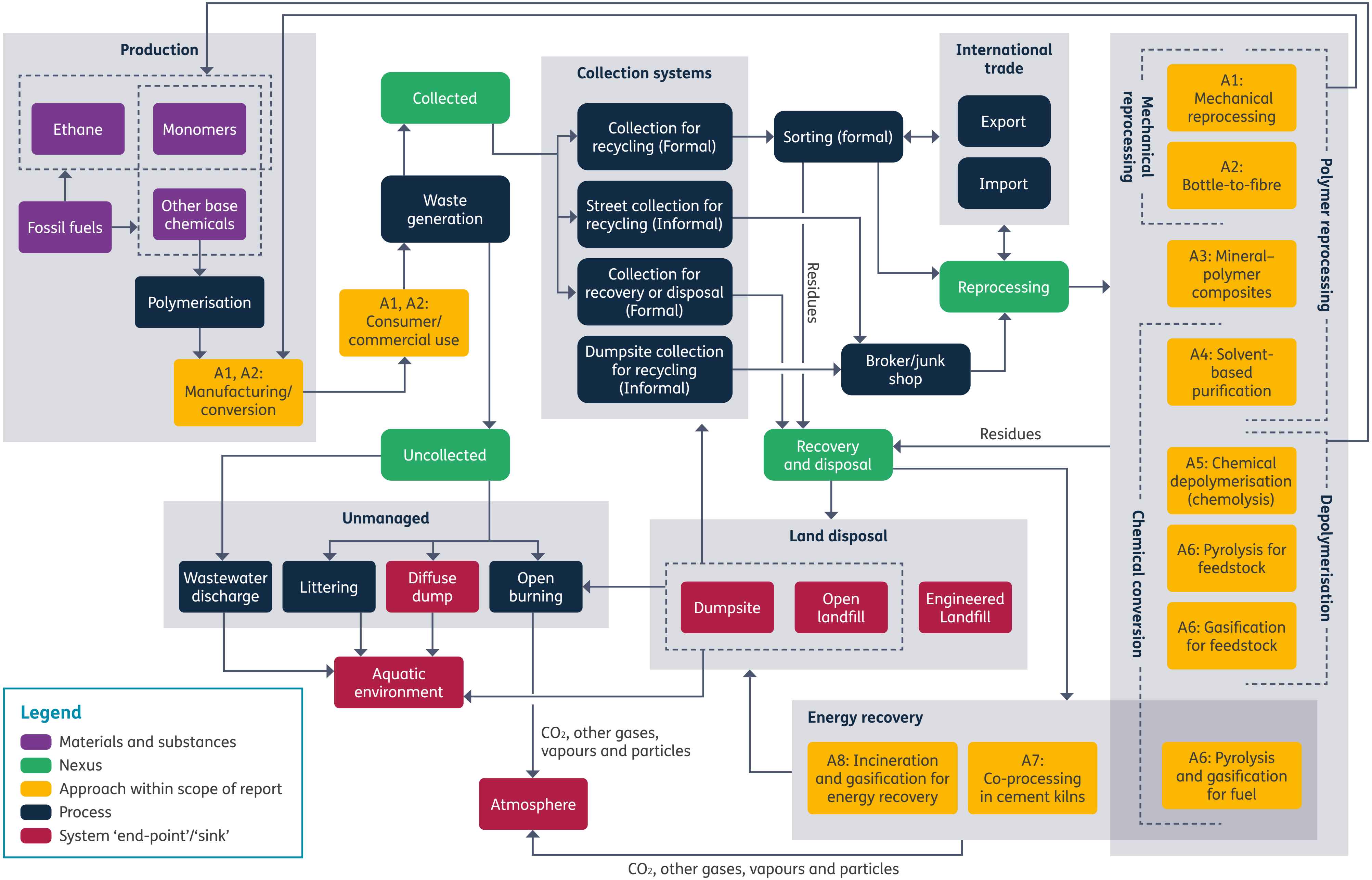
Much of the evidence revealed in this review relates to high-income countries (HICs), however the emphasis of the findings and conclusions focuses on how this evidence relates to the low- and middle-income country context, where the majority of the world's plastic waste mismanagement takes place (Kaza 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)[4] 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.

4 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.[5] 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_2eq 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_2eq emissions. This is projected to increase to 6.5 billion tonnes of CO_2eq by 2050.[6] 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);[7] 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,[8] 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_2eq 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_2eq, 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),[9] 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.

8 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.

9 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).[10] 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^{-1} plastic waste processed as reported by Aryan et al. (2019). If wastewater isn't treated correctly it can contribute to

10 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[11] 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

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_2eq per tonne) (Wang et al., 2015) as virgin polyester (2.2–2.7 tonnes CO_2eq 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; Poulikakos 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_2eq 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'[12] 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.[13] 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)[14] 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).[15] 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.

14 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.

15 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_2), carbon dioxide (CO_2), methane (CH_4) and nitrogen (N_2), alongside other hydrocarbons such as C_2H_4 and C_2H_6 (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).[16]

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).

16 Syngas is mainly comprised of carbon monoxide (CO), hydrogen (H_2), methane (CH_4) and carbon dioxide (CO_2) 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 (Budsaereechai 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_2eq) 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.[17] 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**).

17 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^4 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[18] (778)	Amemiya (2018)
Korea	172 (35)	Bourtsalas et al. (2019)
China	390	Ministry of Housing and Urban–Rural Development (MoHURD) (2019)
India	5[19]	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.

18 It is unclear whether all of these facilities process municipal solid waste.

19 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_2 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.

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.

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 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.

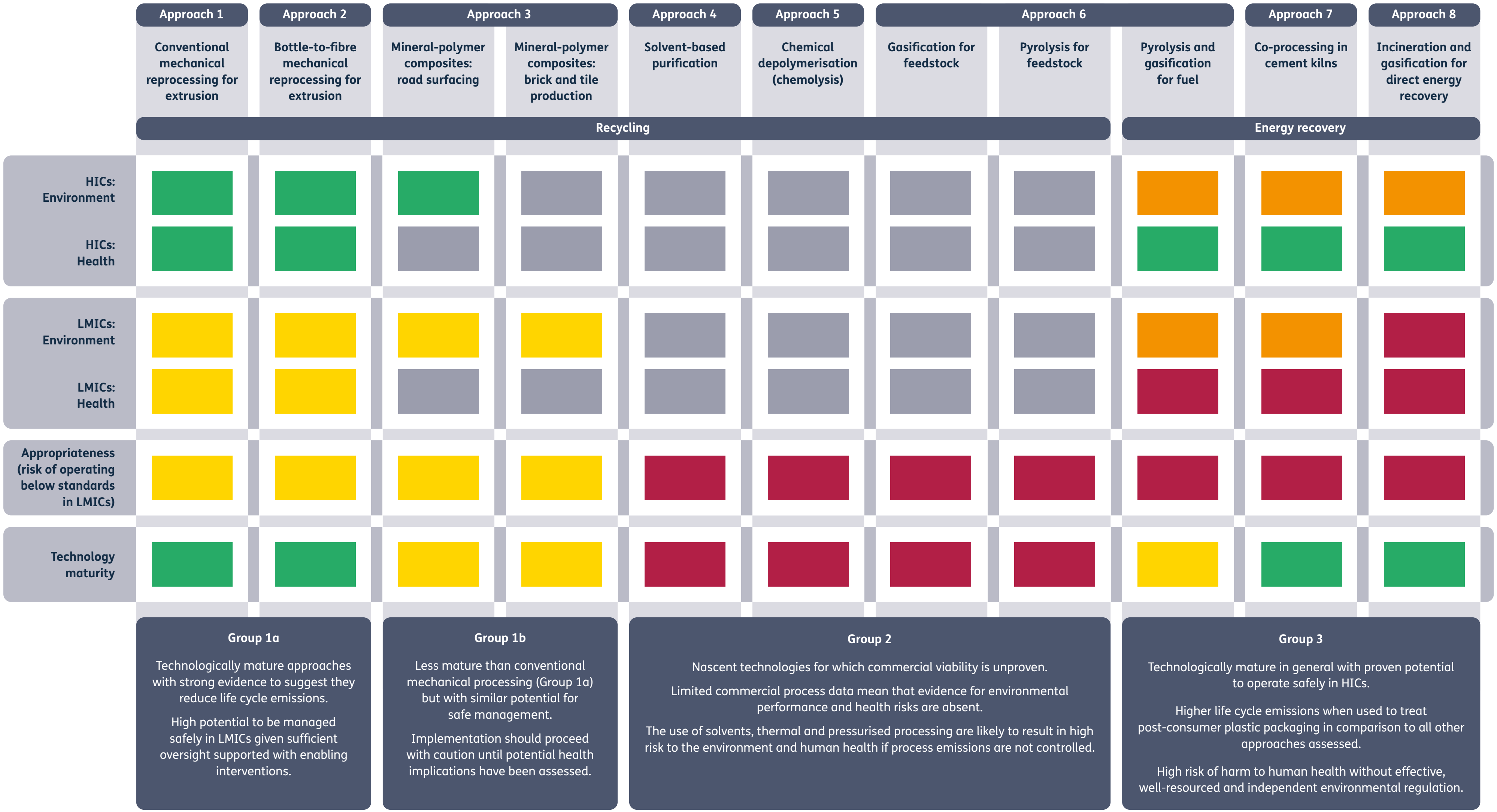


Figure 3: Summary of indicative environmental and health risks, and appropriateness for implementation in LMICs, for approaches to processing post-consumer plastic packaging waste generated by fast-moving consumer goods companies

Abbreviations

HICs - high-income countries

LMICs - low- and middle-income countries

Legend

Environment and health
- low risk
- mid–low risk
- mid–high risk
- high risk
- insufficient data

Appropriateness (risk of operating below standards in LMICs)
- appropriate/low risk of operating below standards
- appropriate but with some risk of operating below standards
- inappropriate but could be implemented if operating standards sufficient
- inappropriate/high risk of operating below standards
- insufficient data

Technology maturity
- high maturity
- mid–high maturity
- mid–low maturity
- low maturity
- insufficient data

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 reprocessors 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.

References

60 Minutes Australia (2019). *Exposing Australia's recycling lie | 60 Minutes Australia.* Retrieved from https://www.youtube.com/watch?v=lqrlEsPoyJk&ab_channel=60MinutesAustralia on 28 December 2020.

Ahmadinia, E., Zargar, M., Karim, M.R., Abdelaziz, M. and Shafigh, P. (2011). Using waste plastic bottles as additive for stone mastic asphalt. *Materials & Design*, 32(10), 4844–4849.

Ali, M., Iqbal, N., Ur Rehman, S., Adil, M. and Anwar, M. (2020). Mechanical Properties of Polyethylene-Sand Blocks Produced from Recycled Plastic Bags. *International Journal of Scientific and Engineering Research,* 11.

Amemiya, T. (2018). Current state and trend of waste and recycling in Japan. *International Journal of Earth & Environmental Sciences*, 3(155).

American Institute for Packaging and the Environment (2018). *Packaging materials management definitions: A review of varying global standards guidance document.* American Institute for Packaging and the Environment (AMERIPEN). Retrieved from: https://cdn.ymaws.com/www.ameripen.org/resource/resmgr/pdfs/AMERIPEN-Report-RecyclingDef.pdf.

Andrady, A.L. and Neal, M.A. (2009). Applications and societal benefits of plastics. *Philosophical transactions of the Royal Society of London. Series B, Biological* sciences, 364(1526), 1977–1984.

Antonetti, E., Iaquaniello, G., Salladini, A., Spadaccini, L., Perathoner, S. and Centi, G. (2017). Waste-to-chemicals for a circular economy: The case of urea production (waste-to-urea). *ChemSusChem*, 10(5), 912–920.

Aryan, Y., Yadav, P. and Samadder, S.R. (2019). Life Cycle Assessment of the existing and proposed plastic waste management options in India: A case study. *Journal of Cleaner Production*, 211, 1268–1283.

Asamany, E.A., Gibson, M.D. and Pegg, M.J. (2017). Evaluating the potential of waste plastics as fuel in cement kilns using bench-scale emissions analysis. *Fuel*, 193, 178–186.

Ashworth, D.C., Elliott, P. and Toledano, M.B. (2014). Waste incineration and adverse birth and neonatal outcomes: a systematic review. *Environment International*, 69, 120–132.

Barabad, M.L.M., Jung, W., Versoza, M.E., Lee, Y.I., Choi, K. and Park, D. (2018). Characteristics of particulate matter and volatile organic compound emissions from the combustion of waste vinyl. *International Journal of Environmental Research and Public Health*, 15(7).

Bartl, A. (2020). Chapter 10 – Textiles production and end-of-life management options. In T.M. Letcher (ed.) *Plastic Waste and Recycling* (251–279): Academic Press.

Basel Convention (nd). Overview. Retrieved from **http://www.basel.int/TheConvention/Overview/tabid/1271/Default.aspx** on 27 June 2021.

BBC News (2020). *UK plastic for "recycling" dumped and burned in Turkey – BBC News*. Retrieved from https://youtu.be/hw6KR2vj_bc on 28 December 2020.

Benedetti, V., Patuzzi, F. and Baratieri, M. (2017). Gasification char as a potential substitute of activated carbon in adsorption applications. *Energy Procedia*, 105, 712–717.

Bernardo, C.A., Simões, C.L. and Pinto, L.M.C. (2016). Environmental and economic life cycle analysis of plastic waste management options. A review. *AIP Conference Proceedings*, 1779(1), 140001.

Bernardo, M., Gonçalves, M., Lapa, N., Barbosa, R., Mendes, B. and Pinto, F. (2012). Characterization of chars produced in the co-pyrolysis of different wastes: Decontamination study. *Journal of Hazardous Materials*, 207–208, 28–35.

Best Current Affairs Center (nd). *Waste to energy plants operational in India*. Retrieved from https://www.bestcurrentaffairs.com/waste-energy-plants-operational-india/ on 10 July 2021.

Bisinella, V., Albizzati, P.F., Astrup, T.F. and Damgaard, A. (2018). *Life cycle assessment of grocery carrier bags*. Report No. 1985. Copenhagen, Denmark: The Danish Environmental Protection Agency. Retrieved from: https://www2.mst.dk/Udgiv/publications/2018/02/978-87-93614-73-4.pdf.

Blasenbauer, D., Huber, F., Lederer, J., Quina, M.J., Blanc-Biscarat, D., Bogush, A., Bontempi, E., Blondeau, J., Chimenos, J.M., Dahlbo, H., Fagerqvist, J., Giro-Paloma, J., Hjelmar, O., Hyks, J., Keaney, J., Lupsea-Toader, M., O'Caollai, C.J., Orupõld, K., Pająk, T., Simon, F.-G., Svecova, L., Šyc, M., Ulvang, R., Vaajasaari, K., Van Caneghem, J., van Zomeren, A., Vasarevičius, S., Wégner, K. and Fellner, J. (2020). Legal situation and current practice of waste incineration bottom ash utilisation in Europe. *Waste Management*, 102, 868–883.

Block, C., Ephraim, A., Weiss-Hortala, E., Minh, D.P., Nzihou, A. and Vandecasteele, C. (2019). Co-pyrogasification of plastics and biomass, a review. *Waste and Biomass Valorization*, 10(3), 483–509.

Boucher, J. and Friot, D. (2017). *Primary microplastics in the oceans: A global evaluation of sources*. Gland, Switzerland: International Union for Conservation of Nature and Natural Resources (IUCN). Retrieved from: https://portals.iucn.org/library/sites/library/files/documents/2017-002-En.pdf.

Bourtsalas, A.C., Seo, Y., Alam, T. and Seo, Y.C. (2019). The status of waste management and waste to energy for district heating in South Korea. *Waste Management*, 85, 304–316.

Bourtsalas, A.C., Zhang, J., Castaldi, M.J. and Themelis, N.J. (2018). Use of non-recycled plastics and paper as alternative fuel in cement production. *Journal of Cleaner Production*, 181, 8–16.

Budsaereechai, S., Hunt, A.J. and Ngernyen, Y. (2019). Catalytic pyrolysis of plastic waste for the production of liquid fuels for engines. *RSC Advances*, 9(10), 5844–5857.

Butler, E., Devlin, G. and McDonnell, K. (2011). Waste polyolefins to liquid fuels via pyrolysis: Review of commercial state-of-the-art and recent laboratory research. *Waste and Biomass Valorization*, 2(3), 227–255.

Carretino Proyectos (2016). *Línea completa de lavado y reciclado de botellas PET*. Retrieved from https://youtu.be/ptDsWKvZgHM on 26 November 2020.

CBC News (2019). *Tracking your plastic: Exposing recycling myths (Marketplace)*. Retrieved from https://youtu.be/c8aVYb-a7Uw on 28 December 2020.

Chen, Y., Cui, Z., Cui, X., Liu, W., Wang, X., Li, X. and Li, S. (2019). Life cycle assessment of end-of-life treatments of waste plastics in China. *Resources, Conservation and Recycling*, 146, 348–357.

Cheng, H. and Hu, Y. (2010). Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China. *Bioresource Technology*, 101(11), 3816–3824.

Chin, C. and Damen, P. (2019). *Viability of using recycled plastics in asphalt and sprayed sealing applications*. Report No. AP-T351-19. Sydney, Australia: Austroads Ltd. Retrieved from: https://austroads.com.au/publications/pavement/ap-t351-19.

Choudhary, K., Sangwan, K.S. and Goyal, D. (2019). Environment and economic impacts assessment of PET waste recycling with conventional and renewable sources of energy. *Procedia CIRP*, 80, 422–427.

Christensen, T.H., Scharff, H. and Hjelmar, O. (2011a). Landfilling: Concepts and challenges. In T.H. Christensen (ed.) *Solid Waste Technology & Management* (685–694). Chichester, UK: Wiley.

Christensen, T.H., Scharff, H. and Hjelmar, O. (2011b). Landfilling: Environmental issues. In T.H. Christensen (ed.) *Solid Waste Technology & Management* (695–708). Chichester, UK: Wiley.

Ciuffi, B., Chiaramonti, D., Rizzo, A.M., Frediani, M. and Rosi, L. (2020). A critical review of SCWG in the context of available gasification technologies for plastic waste. 10(18), 6307.

Cole, G. and Sherrington, C. (2016). *Study to quantify pellet emissions in the UK*. Bristol, UK: Eunomia. Retrieved from: https://www.eunomia.co.uk/reports-tools/study-to-quantify-pellet-emissions-in-the-uk/.

Conesa, J.A., Rey, L., Egea, S. and Rey, M.D. (2011). Pollutant formation and emissions from cement kiln stack using a solid recovered fuel from municipal solid waste. *Environmental Science & Technology*, 45(13), 5878–5884.

Cook, E., Velis, C.A. and Cottom, J. (2022). *Safely recovering value from plastic waste in the Global South: Opportunities and challenges for circular economy and plastic pollution mitigation.* engrXiv, https://doi.org/10.31224/osf.io/tvxem

Cook, E. and Velis, C.A. (2020). *Global review on safer end of engineered life*. London, UK: Royal Academy of Engineering. Retrieved from: https://doi.org/10.5518/100/58.

Cook, E., Velis, C.A. and Derks, M. (2020). Plastic waste reprocessing for circular economy: A systematic review of risks to occupational and public health from legacy substances and extrusion. *engrXiv*, https://doi.org/10.31224/osf.io/yxb5u.

Cook, W., van Bommel, S. and Turnhout, E. (2016). Inside environmental auditing: effectiveness, objectivity, and transparency. *Current Opinion in Environmental Sustainability*, 18, 33–39.

Cooper, C., Booth, A., Varley-Campbell, J., Britten, N. and Garside, R. (2018). Defining the process to literature searching in systematic reviews: a literature review of guidance and supporting studies. *BMC Medical Research Methodology*, 18(1), 85.

Costa, L.M.B., Silva, H.M.R.D., Oliveira, J.R.M. and Fernandes, S.R.M. (2013). Incorporation of waste plastic in asphalt binders to improve their performance in the pavement. *International Journal of Pavement Research and Technology*, 6(4), 457–464.

CreaCycle GmbH (nd). *The CreaSolv® Process*. Retrieved from https://www.creacycle.de/en/the-process.html on 16 January 2021.

Crippa, M., Wilde, B.D., Koopmans, R., Leyssens, J., Linder, M., Muncke, J., Ritschkoff, A.-C., Doorsselaer, K.V., Velis, C. and Wagner, M. (2019). *A circular economy for plastics: Insights from research and innovation to inform policy and funding decisions*. Brussels, Belgium: European Commission. Retrieved from: https://www.hbm4eu.eu/wp-content/uploads/2019/03/2019_RI_Report_A-circular-economy-for-plastics.pdf.

da Costa, J.P., Mouneyrac, C., Costa, M., Duarte, A.C. and Rocha-Santos, T. (2020). The role of legislation, regulatory initiatives and guidelines on the control of plastic pollution. 8(104).

Daharwal, S. (2018). *Waste plastic (polythene bag) recycling plant in Nagpur*. Retrieved from https://youtu.be/0E4SkTcCB8c on 28 August 2021.

Dalager, S. and Reimann, D.O. (2011). Incineration: Mass balances. In T.H. Christensen (ed.) *Solid Waste Technology & Management* (421–429). Chichester, UK: Wiley.

Dalhat, M.A. and Al-Abdul Wahhab, H.I. (2017). Performance of recycled plastic waste modified asphalt binder in Saudi Arabia. *International Journal of Pavement Engineering*, 18(4), 349–357.

Defra (2013). *Advanced thermal treatment of municipal solid waste*. Report No. PB13888. London, UK: Department for Environment, Food & Rural Affairs. Retrieved from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/221035/pb13888-thermal-treatment-waste.pdf.

Doherty, J. (2019). *Work-related ill health 'impacts 4.5% of workers'*. Retrieved from https://www.letsrecycle.com/news/latest-news/work-related-illness-impacts-4-5-of-industry/ on 28 August 2021.

Douglas, P., Freni-Sterrantino, A., Leal Sanchez, M., Ashworth, D.C., Ghosh, R.E., Fecht, D., Font, A., Blangiardo, M., Gulliver, J., Toledano, M.B., Elliott, P., de Hoogh, K., Fuller, G.W. and Hansell, A.L. (2017). Estimating particulate exposure from modern municipal waste incinerators in Great Britain. *Environmental Science & Technology*, 51(13), 7511–7519.

Earth Titan (2019). *6 roof and pavement tiles from plastic waste*. Retrieved from https://youtu.be/ckWqR1JD158 on 26 November 2020.

Edelen, A., Ingwersen, W.W., Rodríguez, C., Alvarenga, R.A.F., de Almeida, A.R. and Wernet, G. (2018). Critical review of elementary flows in LCA data. *The International Journal of Life Cycle Assessment*, 23(6), 1261–1273.

Edwards, C. and Fry, J.M. (2007). *Life cycle assessment of supermarket carrier bags: a review of the bags available in 2006*. Report No. SC030148. Reading, UK: Environment Agency. Retrieved from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/291023/scho0711buan-e-e.pdf.

Ellen MacArthur Foundation (2020). *New Plastics Economy Global Commitment: Commitments, vision and definitions.* Cowes, UK: Ellen MacArthur Foundation. Retrieved from: https://www.ellenmacarthurfoundation.org/assets/downloads/Global-Commitment_Definitions_2020-1.pdf.

Ellen MacArthur Foundation and UN Environment Programme (2020). *The Global Commitment 2020 progress report*. Cowes, UK: Ellen MacArthur Foundation. Retrieved from: https://ellenmacarthurfoundation.org/topics/the-global-commitment/progress-reports.

European Commission (2008). *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives*. Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098.

European Union (2000). *Directive 2000/76/EE of the European Parliament and of the Council Of 4 December 2000 on the Incineration of Waste.* In Off. J. Eur. Union (ed.) L 332/91, 91–111.

Fang, C., Wu, C., Hu, J., Yu, R., Zhang, Z., Nie, L., Zhou, S. and Mi, X. (2014). Pavement properties of asphalt modified with packaging-waste polyethylene. *Journal of Vinyl and Additive Technology*, 20(1), 31–35.

Francis, L.F. (2016a). Chapter 1 – Introduction to materials processing. In L.F. Francis (ed.) *Materials Processing* (1–20). Boston: Academic Press.

Francis, L.F. (2016b). Chapter 2 – Starting materials. In L.F. Francis (ed.) *Materials Processing* (21–103). Boston: Academic Press.

Franklin Associates (2018). *Life cycle impacts of plastic packaging compared to substitutes in the United States and Canada: Theoretical substitution analysis*. Report No. CLIENTS\ACC\KC182695: Franklin Associates – A Division of Eastern Research Group (ERG).

Freni-Sterrantino, A., Ghosh, R.E., Fecht, D., Toledano, M.B., Elliott, P., Hansell, A.L. and Blangiardo, M. (2019). Bayesian spatial modelling for quasi-experimental designs: An interrupted time series study of the opening of Municipal Waste Incinerators in relation to infant mortality and sex ratio. *Environment International*, 128, 109–115.

Georgiopoulou, M. and Lyberatos, G. (2018). Life cycle assessment of the use of alternative fuels in cement kilns: A case study. *Journal of Environmental Management*, 216, 224–234.

Gerassimidou, S., Velis, C.A., Williams, P.T., Castaldi, M.J., Black, L. and Komilis, D. (2020). Chlorine in waste-derived solid recovered fuel (SRF), co-combusted in cement kilns: A systematic review of sources, reactions, fate and implications. *Critical Reviews in Environmental Science and Technology*, 10.1080/10643389.2020.1717298, 1–47.

Geyer, R., Kuczenski, B., Zink, T. and Henderson, A. (2016). Common misconceptions about recycling. *Journal of Industrial Ecology*, 20(5), 1010–1017.

Ghosh, R.E., Freni-Sterrantino, A., Douglas, P., Parkes, B., Fecht, D., de Hoogh, K., Fuller, G., Gulliver, J., Font, A., Smith, R.B., Blangiardo, M., Elliott, P., Toledano, M.B. and Hansell, A.L. (2019). Fetal growth, stillbirth, infant mortality and other birth outcomes near UK municipal waste incinerators; retrospective population based cohort and case-control study. *Environment International*, 122, 151–158.

Giavarini, C. (1994). Chapter 16 – Polymer-modified bitumen. In Yen and Chilingarian (eds.) *Developments in Petroleum Science* (381–400): Elsevier.

GIZ-LafargeHolcim (2020). *Guidelines on pre- and co-processing of waste in cement production: Use of waste as alternative fuel and raw material*. Retrieved from: https://www.giz.de/de/downloads/giz-2020_en_guidelines-pre-coprocessing.pdf.

Gower, R., Green, J. and Williams, M. (2020). *The burning question: Will companies reduce their plastic use?* Tearfund. Retrieved from: https://learn.tearfund.org/-/media/learn/resources/reports/2020-tearfund-the-burning-question-en.pdf.

Gu, F., Guo, J., Zhang, W., Summers, P.A. and Hall, P. (2017). From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study. *Science of The Total Environment*, 601, 1192–1207.

Gu, L. and Ozbakkaloglu, T. (2016). Use of recycled plastics in concrete: A critical review. *Waste Management*, 51, 19–42.

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

Hann, S. and Connock, T. (2020). *Chemical recycling: State of play*. Bristol, UK: Eunomia. Retrieved from: https://www.eunomia.co.uk/reports-tools/final-report-chemical-recycling-state-of-play/.

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

Herbert, L. (2007). *Centenary history of waste and waste managers in London and South East England.* Northampton: Chartered Institution of Wastes Management. Retrieved from: https://bit.ly/3kijLTP.

Hertwich, E.G. (2020). The carbon footprint of material production rises to 23% of global greenhouse gas emissions. *SocArXiv,* 10.31235/osf.io/n9ecw.

Hindenburg Research (2020). *Loop Industries: Former employees and plastics experts blow the whistle on this "Recycled" smoke and mirrors show*. Retrieved from https://hindenburgresearch.com/loop/ on 10 July 2021.

Hjelmar, O., Johnson, A. and Comans, R. (2011a). Incineration: Solid residues. In T.H. Christensen (ed.) *Solid Waste Technology & Management* (430–462). Chichester, UK: Wiley.

IndustrieS, S.S. (2019). Plastic 'Crushing Machine' with Bottle "GRINDER" पुनर्चक्रण की प्रक्रिया / Small Scale IndustrieS. Retrieved from https://youtu.be/kJrYp2PKazE on 26 November 2020.

International Organization for Standardization (2013). *Packaging and the environment – material recycling (ISO standard number: 18604)*. Geneva, Switzerland. Retrieved from: https://bsol.bsigroup.com/Bibliographic/BibliographicInfoData/000000000030230644.

International Power Ecology Company (2014). *Pyrolysis plant disasters*. Retrieved from https://i-pec.ru/en/useful-info/pyrolysis-plant-disasters on 28 August 2021.

Jain, P., Dyson, B., Tolaymat, T. and Ingwersen, W. (2015). *A comparative analysis of life-cycle assessment tools for end-of-life materials management systems.* Report No. EPA/600/R-15/232. Cincinnati, US: United States Environmental Protection Agency – National Risk Management Research Laboratory. Retrieved from: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=310582&Lab=NRMRL.

Jayarama Reddy, P. (2016). *Energy recovery from municipal solid waste by thermal conversion technologies*. London, UK: CRC Press

Jenseit, W., Stahl, H., Wollny, V. and Wittlinger, R. (2003). *Recovery options for plastic parts from end-of-life vehicles: an eco-efficiency assesment*. Brussels, Belgium. Retrieved from: https://www.oeko.de/oekodoc/151/2003-039-en.pdf.

Ji, L., Lu, S., Yang, J., Du, C., Chen, Z., Buekens, A. and Yan, J. (2016). Municipal solid waste incineration in China and the issue of acidification: A review. *Waste Management & Research*, 34(4), 280–297.

Jiao, C. (2020). *The Philippines is making roads and cement with plastic garbage*. Retrieved from https://www.bloomberg.com/news/articles/2020-01-23/the-philippines-is-making-roads-and-cement-with-plastic-garbage on 27 November 2020.

Kadir, A., Syed, S.A., Chun-Yang, Y., Sulaiman, M.R., Chen, X. and El-Harbawi, M. (2013). Incineration of municipal solid waste in Malaysia: Salient issues, policies and waste-to-energy initiatives. *Renewable and Sustainable Energy Reviews*, 24, 181–186.

Kaiser, K., Schmid, M. and Schlummer, M. (2018). Recycling of polymer-based multilayer packaging: A review. 3(1), 1.

Kao, T. (2014). *PET recycling line in Indonesia*. Retrieved from https://youtu.be/ax7OPMOWKCM on 26 November 2020.

Kara, M. (2012). Environmental and economic advantages associated with the use of RDF in cement kilns. *Resources, Conservation and Recycling*, 68, 21–28.

Karelia, G. (2018). *One lakh kilometres of roads in India are being made from plastic waste, is this the solution to end plastic crisis?* Retrieved from https://swachhindia.ndtv.com/plastic-waste-roads-one-lakh-kilometre-india-20274/ on 29 December 2020.

Kaza, S., Yao, L., Bhada-Tata, P. and Van Woerden, F. (2018). *What a waste 2.0: A global snapshot of solid waste management to 2050*. Washington, DC: World Bank Publications. Retrieved from: https://openknowledge.worldbank.org/bitstream/handle/10986/30317/9781464813290.pdf?sequence=12&isAllowed=y.

Khan, M.M.H., Havukainen, J. and Horttanainen, M. (2020). Impact of utilizing solid recovered fuel on the global warming potential of cement production and waste management system: A life cycle assessment approach. *Waste Management & Research*, 10.1177/0734242X20978277, 0734242X20978277.

Khoo, H.H. (2019). LCA of plastic waste recovery into recycled materials, energy and fuels in Singapore. *Resources, Conservation and Recycling*, 145, 67–77.

Klöpffer, W. and Grahl, B. (2014). *Life cycle assessment (LCA): A guide to best practice*. Weinheim, Germany: Wiley.

Kolev, A. (2019). *Plastic sand tile machine – only from recycling plastic and sand*. Retrieved from https://youtu.be/m8zBwvHkwfs on 23 December 2020.

Komly, C.-E., Azzaro-Pantel, C., Hubert, A., Pibouleau, L. and Archambault, V. (2012). Multiobjective waste management optimization strategy coupling life cycle assessment and genetic algorithms: Application to PET bottles. *Resources, Conservation and Recycling*, 69, 66–81.

Kumar, A. and Agrawal, A. (2020). Recent trends in solid waste management status, challenges, and potential for the future Indian cities – A review. *Current Research in Environmental Sustainability*, 2, 100011.

Kumar, R. (2019). *Srinivasa plastic Dana*. Retrieved from https://youtu.be/UVgrgm4oLsM on 26 November 2020.

Kumar, S., Panda, A.K. and Singh, R.K. (2011). A review on tertiary recycling of high-density polyethylene to fuel. *Resources, Conservation and Recycling*, 55(11), 893–910.

Kumi-Larbi, A., Yunana, D., Kamsouloum, P., Webster, M., Wilson, D.C. and Cheeseman, C. (2018). Recycling waste plastics in developing countries: Use of low-density polyethylene water sachets to form plastic bonded sand blocks. *Waste Management,* 80, 112–118.

Kumi-Larbi Jnr, A. (personal communication 10 December 2020). LDPE emissions discussion.

Lardinois, I. and Klundert, A.v.d. (1995). Plastics recycling in developing countries: A booming business? *Gate*, 3(95), 64.

Lassen, C., Hansen, S.F., Magnusson, K., Hartmann, N.B., Jensen, P.R., Nielsen, T.G. and Brinch, A. (2015). *Microplastics: Occurrence, effects and sources of releases to the environment in Denmark*. Report No. 1793, 2015: Danish Environmental Protection Agency. Retrieved from: https://orbit.dtu.dk/en/publications/microplastics-occurrence-effects-and-sources-of-releases-to-the-e.

Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., Thompson, R.C., Jankowska, E., Castillo, A.C., Pilditch, T.D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., Baulch, S., Atreya, M.E., Fischer, D., He, K.K., Petit, M., Sumaila, U.R., Neil, E., Ochocki, M., Lawrence, K. and Palardy, J.E. (2020). Evaluating scenarios toward zero plastic pollution. *Science*, https://doi.org/10.1126/science.aba9475(369), 1455–1461.

Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z. and Christensen, T.H. (2014). Review of LCA studies of solid waste management systems – Part I: Lessons learned and perspectives. *Waste Management*, 34(3), 573–588.

Law, H.J. and Ross, D.E. (2019). International Solid Waste Association's "closing dumpsites" initiative: Status of progress. *Waste Management & Research*, 37(6), 565–568.

Lazarevic, D., Aoustin, E., Buclet, N. and Brandt, N. (2010). Plastic waste management in the context of a European recycling society: Comparing results and uncertainties in a life cycle perspective. *Resources, Conservation and Recycling*, 55(2), 246–259.

Lehne, J. and Preston, F. (2018). *Making concrete change: Innovation in low-carbon cement and concrete*. Chatham House Energy Environment and Resources Department. Retrieved from: https://www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf.

Lenkiewicz, Z. and Webster, M. (2017). *Making waste work: A toolkit – Community waste management in low and middle income countries*. WasteAid. Retrieved from: https://wasteaid.org/toolkit/making-waste-work/.

Lerpiniere, D. and Cook, E. (2018). *Improving markets for recycled plastics: Trends, prospects and policy responses*. Paris, France. Retrieved from: http://dx.doi.org/10.1787/9789264301016-en.

Liang, Y., Tan, Q., Song, Q. and Li, J. (2021). An analysis of the plastic waste trade and management in Asia. *Waste Management*, 119, 242–253.

Lopez, G., Artetxe, M., Amutio, M., Alvarez, J., Bilbao, J. and Olazar, M. (2018). Recent advances in the gasification of waste plastics. A critical overview. *Renewable and Sustainable Energy Reviews*, 82, 576–596.

Lopez, G., Artetxe, M., Amutio, M., Bilbao, J. and Olazar, M. (2017). Thermochemical routes for the valorization of waste polyolefinic plastics to produce fuels and chemicals. A review. *Renewable and Sustainable Energy Reviews*, 73, 346–368.

Louise, N. (2019). *India has built 21,000 miles of road ways using plastic waste*. Retrieved from https://techstartups.com/2019/12/20/india-built-21000-miles-road-ways-using-plastic-waste/ on 31 December 2020.

Ma, Z., Ryberg, M.W., Wang, P., Tang, L. and Chen, W.-Q. (2020). China's import of waste PET bottles benefited global plastic circularity and environmental performance. *Acs Sustainable Chemistry & Engineering*, 8(45), 16861–16868.

Malijonyte, V., Dace, E., Romagnoli, F., Kliopova, I. and Gedrovics, M. (2016). A comparative life cycle assessment of energy recovery from end-of-life tires and selected solid waste. *Energy Procedia*, 95, 257–264.

Martin, E.J.P., Oliveira, D.S.B.L., Oliveira, L.S.B.L. and Bezerra, B.S. (2021). Life cycle comparative assessment of pet bottle waste management options: A case study for the city of Bauru, Brazil. *Waste Management*, 119, 226–234.

Mayer, F., Bhandari, R. and Gäth, S. (2019). Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies. *Science of The Total Environment*, 672, 708–721.

Meys, R., Frick, F., Westhues, S., Sternberg, A., Klankermayer, J. and Bardow, A. (2020). Towards a circular economy for plastic packaging wastes – the environmental potential of chemical recycling. *Resources, Conservation and Recycling*, 162, 105010.

Miandad, R., Rehan, M., Barakat, M.A., Aburiazaiza, A.S., Khan, H., Ismail, I.M.I., Dhavamani, J., Gardy, J., Hassanpour, A. and Nizami, A.-S. (2019). Catalytic pyrolysis of plastic waste: moving toward pyrolysis based biorefineries. 7(27).

Micro Machinery Manufacture (2018). *PP raffia mother baby recycling machine – direct feeding*. Retrieved from PP Raffia Mother Baby Recycling Machine – Direct Feeding Retrieved from https://youtu.be/ylsVh31vwB4 on 26 November 2020.

Ministry of Ecology and Environment (2017). *GB 16487.12 – Environmental protection control standard for solid waste imported as raw materials – Waste and scrap of plastics*. Ministry for Environmental Protection & State Administration for Quality Supervision Inspection and Quarantine Retrieved from: https://bit.ly/2ZcBxjp.

Ministry of Health and Family Welfare (2018). *Food safety and standards (packaging) regulations*. REGD. NO. D. L.-33004/99. New Delhi, India.

Ministry of Housing and Urban–Rural Development (MoHURD) (2019). *2019 Urban construction statistical yearbook*. [Online data set] Ministry of housing and rural development, Retrieved from: http://www.mohurd.gov.cn/xytj/tjzljsxytjgb/jstjnj/w02020123122485271423125000.xls.

Mooge Tech. (2015). *PET washing line, PET bottle recycling machine, PET bottle washing plant*. Retrieved from https://youtu.be/xzO4sISISc4 on 26 Novemeber 2020.

Movilla-Quesada, D., Raposeiras, A.C., Silva-Klein, L.T., Lastra-González, P. and Castro-Fresno, D. (2019). Use of plastic scrap in asphalt mixtures added by dry method as a partial substitute for bitumen. *Waste Management*, 87, 751–760.

MPA Concrete Centre (2017). *Cement sector: joint industry – government industrial decarbonisation and energy efficiency roadmap action plan*. Department for Business, Energy and Industrial Strategy. Retrieved from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/651222/cement-decarbonisation-action-plan.pdf.

Mukherjee, A. (2016). *Life cycle assessment of asphalt mixtures in support of an environmental product declaration*. Houghton, USA. Retrieved from: https://www.asphaltpavement.org/uploads/documents/EPD_Program/LCA_final.pdf.

Muslim, I., Mardiyati and Basuki, A. (2016). Several properties of filament fibers made from recycled bottles of mineral water using melt spinning method. *IOP Conference Series: Materials Science and Engineering*, 105, 012047.

Mutethya, E. (2020). *First African waste-to-energy plant gives Ethiopia breath of fresh air*. Retrieved from https://www.chinadaily.com.cn/a/202002/14/WS5e469b49a310128217277af9.html on 28 August 2021.

Najimesi, L. (2019). *Kenya to construct US $197m incineration plant*. Retrieved from https://constructionreviewonline.com/2019/01/kenya-to-construct-us-197m-incineration-plant/ on 28 August 2021.

Nascimento, F., Gouveia, B., Dias, F., Ribeiro, F. and Silva, M.A. (2020). A method to select a road pavement structure with life cycle assessment. *Journal of Cleaner Production*, 271, 122210.

National Rural Roads Development Agency (nd). *Guidelines for the use of plastic waste in rural roads construction*. National Rural Roads Development Agency Ministry of Rural Development. Retrieved from: https://www.tce.edu/sites/default/files/PDF/Plastic-Roads-Guidelines.pdf.

Neuwahl, F., Cusano, G., Benavides, J.G., Holbrook, S. and Roudier, S. (2019). *Best available techniques (BAT) reference document for waste incineration: Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)*. Report No. EUR 29971 EN. Luxembourg: European Union. Retrieved from: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC118637/jrc118637_wi_bref_2019_published.pdf.

News18 (2019). *All the cities in India that use plastic waste to construct roads – Lucknow, Chennai, Pune and more*. Retrieved from https://www.news18.com/news/auto/all-the-cities-in-india-that-use-plastic-waste-to-construct-roads-lucknow-chennai-pune-and-more-2190445.html on 31 December 2020.

Nielsen, T.D., Hasselbalch, J., Holmberg, K. and Stripple, J. (2020). *Politics and the plastic crisis: A review throughout the plastic life cycle*. 9(1), e360.

Niessen, W.R. (2010). *Combustion and incineration processes: Applications in environmental engineering*. Boca Raton, USA: CRC Press.

Nixon, J.D., Dey, P.K. and Ghosh, S.K. (2017). Energy recovery from waste in India: An evidence-based analysis. *Sustainable Energy Technologies and Assessments,* 21, 23–32.

NTVUganda (2013). *Eco Talk: Plastic tiles*. Retrieved from https://youtu.be/BnEUaNJu8gM on 23 December 2020.

Operation Clean Sweep (2020). *PlasticsEurope Operation Clean Sweep®: Report 2019*. Brussels, Belgium: PlasticsEurope AISBL. Retrieved from: http://www.opcleansweep.eu/wp-content/uploads/2020/10/OCS-Progress-Report-2019-Web-LR-151020.pdf.

PackagingLaw.com (2019). U*pdate: Food packaging regulations in Latin America*. Retrieved from https://www.packaginglaw.com/special-focus/update-food-packaging-regulations-latin-america on 3 January 2021.

PackagingLaw.com (2020). *Thailand considers allowing recycled food-contact plastic, requests information*. Retrieved from https://www.packaginglaw.com/news/thailand-considers-allowing-recycled-food-contact-plastic-requests-information on 23 December 2020.

Park, S.H. and Kim, S.H. (2014). Poly (ethylene terephthalate) recycling for high value added textiles. *Fashion and Textiles*, 1(1), 1.

Parkes, B., Hansell, A.L., Ghosh, R.E., Douglas, P., Fecht, D., Wellesley, D., Kurinczuk, J.J., Rankin, J., de Hoogh, K., Fuller, G.W., Elliott, P. and Toledano, M.B. (2020). Risk of congenital anomalies near municipal waste incinerators in England and Scotland: Retrospective population-based cohort study. *Environment International*, 134, 104845.

Patagonia (nd). *Recycled Polyester*. Retrieved from https://www.patagonia.com/our-footprint/recycled-polyester.html on 3 July 2021.

Petco (nd). *Industry projects: The subsidy mechanism.* Retrieved from https://petco.co.za/petco-industry-projects/ on 3 January 2021.

PetStar (2018). *Sustainability report 2018*. Retrieved from https://www.petstar.mx/media/1862/informe-de-sustentabilidad-ingles-2018-version-final.pdf on 21 October 2021

Potdar, R. (2015). *Plastic recycling machine | plastic recycling plant | plastic reprocessing machin*e. Retrieved from https://youtu.be/VJrkdAmx-2s on 26 November 2020.

Poulikakos, L.D., Papadaskalopoulou, C., Hofko, B., Gschösser, F., Cannone Falchetto, A., Bueno, M., Arraigada, M., Sousa, J., Ruiz, R., Petit, C., Loizidou, M. and Partl, M.N. (2017). Harvesting the unexplored potential of European waste materials for road construction. *Resources, Conservation and Recycling*, 116, 32–44.

Provencher, J.F., Liboiron, M., Borrelle, S.B., Bond, A.L., Rochman, C., Lavers, J.L., Avery-Gomm, S., Yamashita, R., Ryan, P.G., Lusher, A.L., Hammer, S., Bradshaw, H., Khan, J. and Mallory, M.L. (2020). A Horizon Scan of research priorities to inform policies aimed at reducing the harm of plastic pollution to biota. *Science of The Total Environment*, 733, 139381.

Punkkinen, H., Oasmaa, A., Laatikainen-Luntama, J., Nieminen, M. and Laine-Ylijoki, J. (2017). *Thermal conversion of plastic containing waste: A review*. Report No. D4.1-22. Helsinki, Finland: Arvi material value chains. Retrieved from: http://arvifinalreport.fi/files/Thermal%20conversion%20of%20plastic-containing%20waste%20A%20review.pdf.

Quicker, P. (2019). Evaluation of recent developments regarding alternative thermal waste treatment with a focus on depolymerisation processes. *IRRC Waste-to-Energy*, 9, 43.

Ragaert, K., Delva, L. and Van Geem, K. (2017). Mechanical and chemical recycling of solid plastic waste. *Waste Management*, 69, 24–58.

RAHA Bitumen Co. (nd). *Polymer modified bitumen.* Retrieved from http://rahabitumen.com/polymer-modified-bitumen/ on 29 December 2020.

Raheem, A.B., Noor, Z.Z., Hassan, A., Abd Hamid, M.K., Samsudin, S.A. and Sabeen, A.H. (2019). Current developments in chemical recycling of post-consumer polyethylene terephthalate wastes for new materials production: A review. *Journal of Cleaner Production*, 225, 1052–1064.

Rajendran, S., Hodzic, A., Scelsi, L., Hayes, S., Soutis, C., AlMa'adeed, M. and Kahraman, R. (2013). Plastics recycling: Insights into life cycle impact assessment methods. *Plastics, Rubber and Composites*, 42(1), 1–10.

RDC-Environment (2010). *Analyse du cycle de vie d'une bouteille PET*. Brussels, Belgium: Valorplast and Eco-Emballages. Retrieved from: http://www.ecoemballages.fr/fileadmin/contribution/pdf/instit/etudes/ACV_bouteille_PET-2010.pdf.

Ren, Y., Shi, L., Bardow, A., Geyer, R. and Suh, S. (2020). Life-cycle environmental implications of China's ban on post-consumer plastics import. *Resources, Conservation and Recycling*, 156, 104699.

Republic Cement (2020). *Republic Cement expands partnership with Nestlé Philippines*. Retrieved from https://republiccement.com/republic-cement-nestle-2020/ on 27 November 2020.

Reyna-Bensusan, N., Wilson, D.C. and Smith, S.R. (2018). Uncontrolled burning of solid waste by households in Mexico is a significant contributor to climate change in the country. *Environmental Research,* 163, 280–288.

Rødland, E. (2019). Ecotoxic potential of road-associated microplastic particles (RAMP). *Vann*, 54(3), 166–183.

Rodríguez, J.R. (2012). The Monte Testaccio. From rubbish dump to archive. *Atti della Pontificia Accademia Romana di Archeologia: Serie III, Rendiconti*, 111–128.

Rollinson, A.N. and Oladejo, J. (2020). *Chemical recycling: status, sustainability, and environmental impacts*. Berkley, USA: Global Alliance for Incinerator Alternatives (GAIA). Retrieved from: https://www.no-burn.org/cr-technical-assessment/.

Rollinson, A.N. and Oladejo, J.M. (2019). 'Patented blunderings', efficiency awareness, and self-sustainability claims in the pyrolysis energy from waste sector. *Resources, Conservation and Recycling*, 141, 233–242.

Rosato, D. (2020). *Emerging global food packaging regulation trends*. Retrieved from https://omnexus.specialchem.com/tech-library/article/emerging-global-food-packaging-regulation-trends on 28 December 2020.

Rovira, J., Mari, M., Nadal, M., Schuhmacher, M. and Domingo, J.L. (2010). Partial replacement of fossil fuel in a cement plant: Risk assessment for the population living in the neighborhood. *Science of The Total Environment,* 408(22), 5372–5380.

Rovira, J., Nadal, M., Schuhmacher, M. and Domingo, J.L. (2016). Alternative fuel implementation in a cement plant: Human health risks and economical valuation. *Archives of Environmental Contamination and Toxicology*, 71(4), 473–484.

Saha, G.K. (2020). E*ver Bright Plastic Co. factory introduction: PET bottle flakes – Plastic bottle recycling*. Retrieved from https://youtu.be/C10hhjhVRDI on 26 November 2020.

Salvi, S., Mantute, K., Sabale, R., Lande, S., Kadlag, A. and Professor, A. (2021). *A Study of waste plastic used in paving block.* 2320–2882.

Santos, J., Cerezo, V., Soudani, K. and Bressi, S. (2018). A comparative life cycle assessment of hot mixes asphalt containing bituminous binder modified with waste and virgin polymers. *Procedia CIRP*, 69, 194–199.

Sarioğlu, E. and Kaynak, H.K. (2018). PET bottle recycling for sustainable textiles. In N.O. Camlibel (ed.) *Polyester – production, characterization and innovative applications*. Online: IntechOpen.

Schmidt, A., Kløverpris, N.H., Bakas, I., Kjær, B.J., Vogt, R. and Giegrich, J. (2009). *Comparative life cycle assessment of two options for waste tyre treatment: material recycling versus civil engineering applications – Executive summary*. Retrieved from: https://www.resource-recovery.net/sites/default/files/lca_-_material_recycling_vs._co-incineration_in_cement_kilns_0.pdf.

Schorcht, F., Kourti, I., Scalet, B.M., Roudier, S. and Sancho, L.D. (2013). *Best available techniques (BAT) reference document for the production of cement, lime and magnesium oxide: Industrial emissions directive 2010/75/EU integrated pollution prevention and control.* Report No. EUR 26129 EN. Luxembourg: European Commission Joint Research Centre. Retrieved from: https://eippcb.jrc.ec.europa.eu/reference/production-cement-lime-and-magnesium-oxide.

Schwarz, A.E., Ligthart, T.N., Godoi Bizarro, D., De Wild, P., Vreugdenhil, B. and van Harmelen, T. (2021). Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. *Waste Management*, 121, 331–342.

Schyns, Z.O.G. and Shaver, M.P. (2020). Mechanical Recycling of Packaging Plastics: A Review. *Macromolecular Rapid Communications,* https://doi.org/10.1002/marc.202000415, 2000415.

Secretariat of the Basel Convention (2019). *BC-14/12: Amendments to Annexes II, VIII and IX to the Basel Convention.* United Nations Environment Programme. Retrieved from: http://www.basel.int/Implementation/MarinePlasticLitterandMicroplastics/Overview/tabid/6068/Default.aspx.

Seo, Y.C., Alam, M.T. and Yang, W.S. (2018). Gasification for low-grade feedstock. In Y. Yun (ed.) *Gasification of municipal solid waste: Intechopen.*

Séverin, M., Velis, C.A., Longhurst, P.J. and Pollard, S.J.T. (2010). The biogenic content of process streams from mechanical–biological treatment plants producing solid recovered fuel. Do the manual sorting and selective dissolution determination methods correlate? *Waste Management*, 30(7), 1171–1182.

Sharuddin, S.D.A., Abnisa, F., Daud, W.M.A.W. and Aroua, M.K. (2016). A review on pyrolysis of plastic wastes. *Energy Conversion and Management*, 115, 308–326.

Shen, L., Nieuwlaar, E., Worrell, E. and Patel, M.K. (2011). Life cycle energy and GHG emissions of PET recycling: change-oriented effects. *The International Journal of Life Cycle Assessment,* 16(6), 522–536.

Shen, L., Worrell, E. and Patel, M.K. (2010). Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling. *Resources, Conservation and Recycling,* 55(1), 34–52.

Sherwood, J. (2020). Closed-Loop Recycling of Polymers Using Solvents: Remaking plastics for a circular economy. *Johnson Matthey Technology Review,* 64(1), 4–15.

Shonfield, P. (2008). LCA of management options for mixed waste plastics. Banbury, UK Waste and Resource Action Programme (WRAP)

Singh, M. (2018). *Plastic scrap reprocessing and washing plant* (www.manjeetengineers.com) 9810072849. Retrieved from https://youtu.be/v-eBTSXxjqc on 26 November 2020.

Sky News (2018). *Dirty business: What really happens to your recycling.* Retrieved from https://youtu.be/oRQLilXLAIU on 28 December 2020.

Solis, M. and Silveira, S. (2020). Technologies for chemical recycling of household plastics – A technical review and TRL assessment. *Waste Management,* 105, 128–138.

Spath, P.L., Mann, M.K. and Kerr, D.R. (1999). *Life cycle assessment of coal-fired power production.* Report No. NREL/TP-570-25119. Colorado, USA: National Renewable Energy Laboratory. Retrieved from: https://www.nrel.gov/docs/fy99osti/25119.pdf.

sps, s. (2018a). *Plastic re use, easy machines.* Retrieved from https://youtu.be/dAUb9w28YR4 on 28 August 2021.

sps, s. (2018b). *Plastic recycling easy process.* Retrieved from https://youtu.be/t0zovkNfZjs on 28 August 2021.

Straker, K., Peel, S., Nusem, E. and Wrigley, C. (2021). Designing a dangerous unicorn: Lessons from the Theranos case. *Business Horizons,* 64(4), 525–536.

SYSTEMIQ and The Pew Charitable Trust (2020). *Breaking the plastic wave.* UK: The Pew Charitable Trust. Retrieved from: https://www.pewtrusts.org/-/media/assets/2020/07/breakingtheplasticwave_report.pdf.

Tang, Z., Huang, Q., Cheng, J., Yang, Y., Yang, J., Guo, W., Nie, Z., Zeng, N. and Jin, L. (2014). Polybrominated diphenyl ethers in soils, sediments, and human hair in a plastic waste recycling area: A neglected heavily polluted area. *Environmental Science and Technology,* 48(3), 1508–1516.

Tang, Z.W., Zhang, L.Z., Huang, Q.F., Yang, Y.F., Nie, Z.Q., Cheng, J.L., Yang, J., Wang, Y.W. and Chai, M. (2015). Contamination and risk of heavy metals in soils and sediments from a typical plastic waste recycling area in North China. *Ecotoxicology and Environmental Safety,* 122, 343–351.

Tearfund (2020). Principles to guide fair partnerships on plastics between the informal waste sector and fast-moving consumer goods companies update, Unpublished voluntary agreement.

Textile Exchange (2019). *Preferred fiber & materials market report 2019.* Textile Exchange. Retrieved from: https://store.textileexchange.org/wp-content/uploads/woocommerce_uploads/2019/11/Textile-Exchange_Preferred-Fiber-Material-Market-Report_2019.pdf.

The Times of India (2019). *Waste Warriors: This startup turns waste into public good.* Retrieved from https://youtu.be/mQ93IcGCag4 on 26 November 2020.

The World Bank (2013). *In Azerbaijan: Managing waste safely.* Retrieved from https://www.worldbank.org/en/results/2013/08/21/in-azerbaijan-managing-waste-safely on 10 July 2021.

Thiounn, T. and Smith, R.C. (2020). Advances and approaches for chemical recycling of plastic waste. *Journal of Polymer Science,* 58(10), 1347–1364.

Thorneycroft, J., Orr, J., Savoikar, P. and Ball, R.J. (2018). Performance of structural concrete with recycled plastic waste as a partial replacement for sand. *Construction and Building Materials,* 161, 63–69.

Tillman, A.M., Ekvall, T., Baumann, H. and Rydberg, T. (1998). *Choice of system boundaries in life cycle assessment.*

Triwood1973 (2009). *How plastic bottles are recycled into polyester.* Retrieved from https://youtu.be/zyF9MxlcItw on 26 November 2020.

Tsai, C.J., Chen, M.L., Chang, K.F., Chang, F.K. and Mao, I.F. (2009). The pollution characteristics of odor, volatile organochlorinated compounds and polycyclic aromatic hydrocarbons emitted from plastic waste recycling plants. *Chemosphere*, 74(8), 1104–1110.

Turconi, R., Boldrin, A. and Astrup, T. (2013). Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renewable and Sustainable Energy Reviews,* 28, 555–565.

Ügdüler, S., Van Geem, K.M., Roosen, M., Delbeke, E.I.P. and De Meester, S. (2020). Challenges and opportunities of solvent-based additive extraction methods for plastic recycling. *Waste Management,* 104, 148–182.

UNEP and Basel Convention (2020a). *Basel Convention on the control of transboundary movements of hazardous wastes and their disposal: Protocol on liability and compensation for damage resulting from transboundary movements of hazardous wastes and their disposal texts and annexes revised in 2019.* United Nations Environment Programme (UNEP). Retrieved from: http://www.basel.int/Portals/4/download.aspx?d=UNEP-CHW-IMPL-CONVTEXT.English.pdf.

UNEP and Basel Convention (2020b). *Draft updated technical guidelines on the identification and environmentally sound management of plastic wastes and for their disposal. Geneva, Switzerland: UNEP.* Retrieved from: http://www.basel.int/TheConvention/OpenendedWorkingGroup(OEWG)/Meetings/OEWG12/Overview/tabid/8264/Default.aspx.

Unilever (nd). *Waste & packaging*. Retrieved from https://www.unilever.co.uk/sustainable-living/waste-and-packaging/ on 16 January 2021.

United States Environmental Protection Agency (2019). *Energy recovery from the combustion of municipal solid waste (MSW).* Retrieved from https://www.epa.gov/smm/energy-recovery-combustion-municipal-solid-waste-msw on 28 August 2021.

Unwin, J., Coldwell, M.R., Keen, C. and McAlinden, J.J. (2013). Airborne emissions of carcinogens and respiratory sensitizers during thermal processing of plastics. *The Annals of Occupational Hygiene,* 57(3), 399–406.

Uvarajan, T., Gani, P., Chuan, N.C. and Zulkernain, N.H. (2021). Reusing plastic waste in the production of bricks and paving blocks: a review. European *Journal of Environmental and Civil Engineering*, 10.1080/19648189.2021.1967201, 1–34.

Valavanidis, A., Iliopoulos, N., Gotsis, G. and Fiotakis, K. (2008). Persistent free radicals, heavy metals and PAHs generated in particulate soot emissions and residue ash from controlled combustion of common types of plastic. *Journal of Hazardous Materials,* 156(1-3), 277–284.

Vasudevan, R., Ramalinga Chandra Sekar, A., Sundarakannan, B. and Velkennedy, R. (2012). A technique to dispose waste plastics in an ecofriendly way – Application in construction of flexible pavements. *Construction and Building Materials,* 28(1), 311–320.

Velis, C.A. and Cook, E. (2021). Mismanagement of plastic waste through open burning with emphasis on the Global South: A systematic review of risks to occupational and public health. *Environmental Science & Technology,* 10.1021/acs.est.0c08536.

Vermeulen, I., Caneghem, J.v., Block, C. and Vandecasteele, C. (2009). *Comparison of the environmental impact of the incineration of calorific industrial waste in a rotary kiln and a cement kiln in view of fuel substitution. Heverlee, Belgium: Katholieke Universiteit Leuven.* Retrieved from: https://www.eurits.org/docs/KUL-study-incineration-coincineration.pdf.

Vila-Cortavitarte, M., Lastra-González, P., Calzada-Pérez, M.Á. and Indacoechea-Vega, I. (2018). Analysis of the influence of using recycled polystyrene as a substitute for bitumen in the behaviour of asphalt concrete mixtures. *Journal of Cleaner Production,* 170, 1279–1287.

Vogelsang, C., Lusher, A.L., Dadkhah, M.E., Sundvor, I., Umar, M., Ranneklev, S.B., Eidsvoll, D. and Meland, S. (2020). *Microplastics in road dust – characteristics, pathways and measures.* Report No. 7526-2020. Oslo, Norway: N. I. f. W. Research. Retrieved from: https://niva.brage.unit.no/niva-xmlui/handle/11250/2493537.

Wagner, S. and Schlummer, M. (2020). Legacy additives in a circular economy of plastics: Current dilemma, policy analysis, and emerging countermeasures. *Resources, Conservation and Recycling,* 158, 104800.

Wahab, D.A., Abidin, A. and Azhari, C.H. (2007). Recycling trends in the plastics manufacturing and recycling companies in Malaysia. *Journal of Applied Sciences,* 7(7), 1030–1035.

Walker, T.W., Frelka, N., Shen, Z., Chew, A.K., Banick, J., Grey, S., Kim, M.S., Dumesic, J.A., Van Lehn, R.C. and Huber, G.W. (2020). Recycling of multilayer plastic packaging materials by solvent-targeted recovery and precipitation. *Science Advances,* 6(47), eaba7599.

Walsh, D.C. (2002). The evolution of refuse: Incineration: What led to the rise and fall of incineration in New York City? *Environmental Science and Technology,* https://pubs.acs.org/doi/pdfplus/10.1021/es022400n.

Wang, C., Wang, L., Liu, X., Du, C., Ding, D., Jia, J., Yan, Y. and Wu, G. (2015). Carbon footprint of textile throughout its life cycle: a case study of Chinese cotton shirts. *Journal of Cleaner Production,* 108, 464–475.

Wang, Z., Richter, H., Howard, J.B., Jordan, J., Carlson, J. and Levendis, Y.A. (2004). Laboratory investigation of the products of the incomplete combustion of waste plastics and techniques for their minimization. *Industrial & Engineering Chemistry Research,* 43(12), 2873–2886.

White, G. (2019). Evaluating recycled waste plastic modification and extension of bituminous binder for asphalt. Proceedings 18th Annual International Conference on Pavement Engineering, Asphalt Technology and Infrastructure. Retrieved from: https://www.macrebur.com/pdfs/product/Liverpool%20-%20Waste%20plastic%20evaluation%20Ver%202.pdf.

White, G. and Reid, G. (2018). Recycled waste plastic modification of bituminous binder. *8th Symposium on Pavement Surface Characteristics: SURF 2018 – Vehicle to Road Connectivity*. Retrieved from: https://www.macrebur.com/pdfs/product/SURF%20-%20Plastic%20Recycling%20for%20Bitumen%20Ver%204.pdf.

Wiedinmyer, C., Yokelson, R.J. and Gullett, B.K. (2014). Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste. *Environmental Science & Technology,* 48(16), 9523–9530.

Williams, P.T. and Williams, E.A. (1999). Interaction of plastics in mixed-plastics pyrolysis. *Energy & Fuels,* 13(1), 188–196.

Wolfesberger, U., Aigner, I. and Hofbauer, H. (2009). Tar content and composition in producer gas of fluidized bed gasification of wood – Influence of temperature and pressure. *Environmental Progress & Sustainable Energy,* 28(3), 372–379.

Wu, J.S. (2018). *Capital cost comparison of waste-to-energy (WTE) facilities in China and the US.* (Master of Science in Earth and Environmental Engineering, Columbia University, Fu Foundation School of Engineering and Applied Science). Retrieved from: http://gwcouncil.org/wp-content/uploads/2018/07/Jane-Wu_thesis.pdf.

Wu, S. and Montalvo, L. (2021). Repurposing waste plastics into cleaner asphalt pavement materials: A critical literature review. *Journal of Cleaner Production,* 280, 124355.

Yamashita, K., Yamamoto, N., Mizukoshi, A., Noguchi, M., Ni, Y. and Yanagisawa, Y. (2009). Compositions of volatile organic compounds emitted from melted virgin and waste plastic pellets. *Journal of the Air and Waste Management Association,* 59(3), 273–278.

Zeng, X., Ueki, Y., Yoshiie, R., Naruse, I., Wang, F., Han, Z. and Xu, G. (2020). Recent progress in tar removal by char and the applications: A comprehensive analysis. C*arbon Resources Conversion,* 3, 1–18.

Zhang, R., Ma, X., Shen, X., Zhai, Y., Zhang, T., Ji, C. and Hong, J. (2020). PET bottles recycling in China: An LCA coupled with LCC case study of blanket production made of waste PET bottles. *Journal of environmental management,* 260, 110062.

Zhang, Y., Kang, H., Hou, H., Shao, S., Sun, X., Qin, C. and Zhang, S. (2018). Improved design for textile production process based on life cycle assessment. *Clean Technologies and Environmental Policy,* 20(6), 1355–1365.

Zhao, Y.B., Lv, X.D. and Ni, H.G. (2018). Solvent-based separation and recycling of waste plastics: A review. *Chemosphere*, 209, 707–720

Zheng, J. and Suh, S. (2019). Strategies to reduce the global carbon footprint of plastics. *Nature Climate Change,* 9(5), 374–378.

Zhu, J., Birgisson, B. and Kringos, N. (2014). Polymer modification of bitumen: Advances and challenges. *European Polymer Journal,* 54, 18–38.

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

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

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

Subsection	Research questions
Overview	• How much material is treated by this approach? • What is the technological maturity?
Environment	• What are the climate change impacts or avoided burdens? • Does this process have any impacts on biological populations, assemblages or ecosystems? • What would improve the environmental performance?
Health	• What are the potential impacts on the health, safety and welfare of workers engaged in the activity? • What are the potential effects of the process or activity on public health? • What would make this approach safe?[20]

20 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
• Conventional plastics • Technologies listed • Supply systems • Post-consumer plastic waste • Packaging • Peer reviewed journal articles, conference papers, books, Reports, websites, online multi-media	• Waste collection – eg waste pickers • Biodegradable plastics • International trade in plastic scrap • Post-industrial waste • Non-packaging • Reuse/alternative delivery systems • Film footage intended to expose poor practice

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.

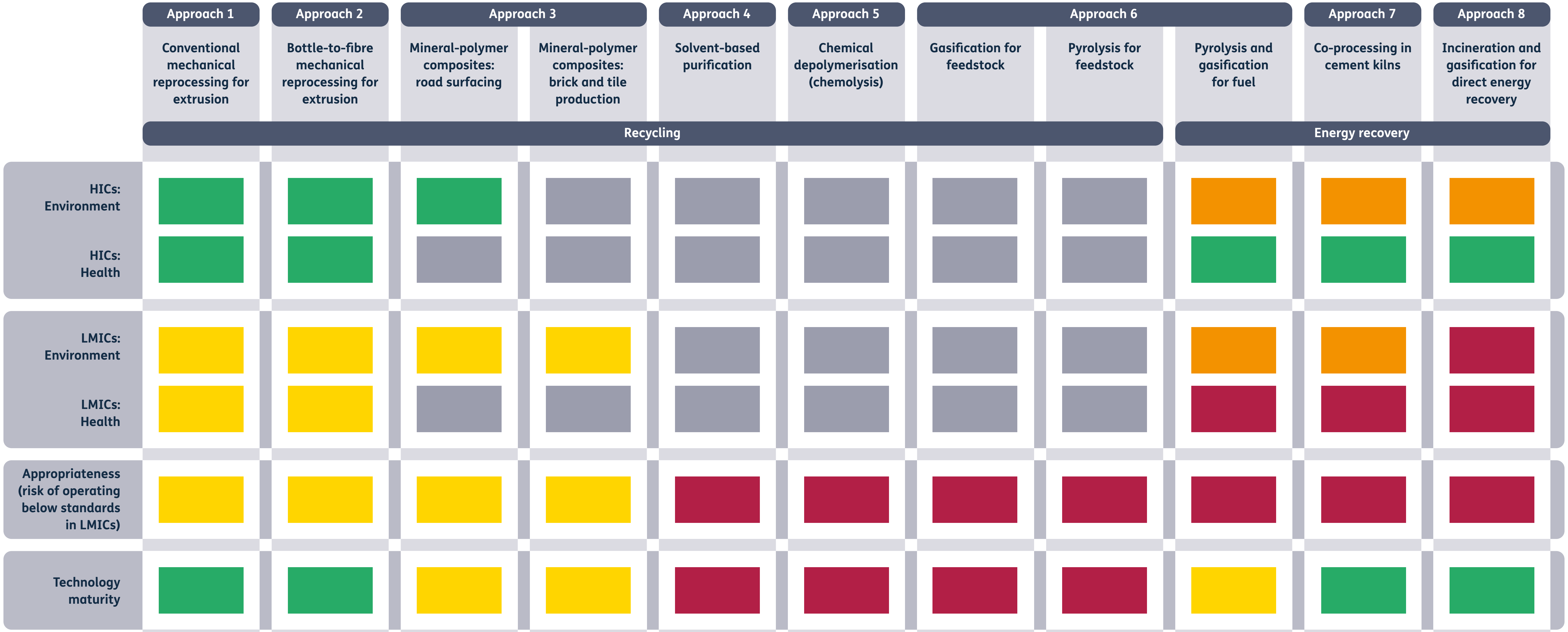
As well as recording basic information about each process, a visual assessment of hazards was made which were grouped as follows:

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

learn.tearfund.org
Tearfund, 100 Church Road, Teddington, TW11 8QE, United Kingdom
+44 (0)20 3906 3906 publications@tearfund.org

Registered office: Tearfund, 100 Church Road, Teddington, TW11 8QE. Registered in England: 994339. A company limited by guarantee. Registered Charity No. 265464 (England & Wales) Registered Charity No. SC037624 (Scotland)
J584 – (1021)

tearfund



Group 1a

Technologically mature approaches with strong evidence to suggest they reduce life cycle emissions.

High potential to be managed safely in LMICs given sufficient oversight supported with enabling interventions.

Group 1b

Less mature than conventional mechanical processing (Group 1a) but with similar potential for safe management.

Implementation should proceed with caution until potential health implications have been assessed.

Group 2

Nascent technologies for which commercial viability is unproven.

Limited commercial process data mean that evidence for environmental performance and health risks are absent.

The use of solvents, thermal and pressurised processing are likely to result in high risk to the environment and human health if process emissions are not controlled.

Group 3

Technologically mature in general with proven potential to operate safely in HICs.

Higher life cycle emissions when used to treat post-consumer plastic packaging in comparison to all other approaches assessed.

High risk of harm to human health without effective, well-resourced and independent environmental regulation.

Legend

Environment and health
- low risk
- mid–low risk
- mid–high risk
- high risk
- insufficient data

Appropriateness (risk of operating below standards in LMICs)
- appropriate/low risk of operating below standards
- appropriate but with some risk of operating below standards
- inappropriate but could be implemented if operating standards sufficient
- inappropriate/high risk of operating below standards
- insufficient data

Technology maturity
- high maturity
- mid–high maturity
- mid–low maturity
- low maturity
- insufficient data

Abbreviations

HICs - high-income countries

LMICs - low- and middle-income countries