UN environment programme

Life cycle assessment (LCA) on feasibility of plastic waste recycling technologies in Asia

Cambodia LCA report

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Executive summary

UNEP's International Environmental Technology Centre (IETC) wishes to fully understand the environmental impacts of recycling technologies being implemented by small and medium enterprises (SMEs), or potentially being implemented by SMEs, to ensure that the recycling technologies and methods employed are environmentally sustainable and align with circular economy principals. Life cycle assessment (LCA) – with its ability to cover the whole value chain and take a wide range of potential environmental impacts into account – was chosen for the assessment, to assesses the most sustainable options for SMEs, as well as how sustainability can be improved over time.

The goal of the LCA is thus to quantify the life cycle environmental impacts of plastic recycling technologies and other plastic waste management options in Cambodia, with the view of identifying sustainable technologies available to SMEs and how best to improve sustainability going forward. The study is a "gate-to-grave" LCA and focusses only on the end-of-life management of plastic waste. As such, the life cycle system covers everything required to manage plastic waste at end-of-life and includes plastic waste collection, transport to disposal/recyclers, pre-processing (sorting, baling etc.) and end-of-life management processing (landfilling, incineration or recycling), along with the avoided processes (virgin plastic production or electricity generation) where relevant. The end-of-life management options covered by the study are:

- Status-quo plastic waste management (i.e. current split between open burning, dumping, landfilling, incineration, recycling etc.)
- Controlled landfilling
- Incineration with energy recovery (i.e. energy recovery in the form of electricity)
- Production of refuse derived fuel (RDF) (i.e. energy recovery in the form of fuel)
- Mechanical recycling
    - Current low-technology mechanical recycling employed by SMEs
    - Higher-technology open-loop mechanical recycling
    - Closed-loop mechanical recycling of polyethylene terephthalate (rPET)

The functional unit for the study, which is the product or service unit against which environmental impacts are measured, is 1,000 kg of plastic waste managed at end-of-life.

The IMPACT World+ impact assessment method, which includes 25 impact categories, is applied in the study, with normalization, weighting and aggregation of the human health and ecosystem quality impact categories applied to aid interpretation. Results are therefore presented for four disaggregated impact categories (short- and long-term climate change, water scarcity, and fossil and nuclear energy use, as well as two aggregated areas of protection (AoP – human health and ecosystem quality). Alongside these LCA impact categories, results are also presented for the plastic footprint and material circularity indicator (MCI), in order to estimate the plastic leaked into the environment from each system and the circularity of each management option.

Data for the LCA model are sourced primarily from secondary data sources, with key inputs - recycling transport distances, recycling yields and selected recycling process inputs (electricity, potassium aluminium sulphate and sodium hydroxide) – for SME low-technology recycling collected from Cambodian recycling sector stakeholders. Secondary data used for low-technology recycling, including the overall recycling value chain, is carefully chosen to be representative of the SME recycling sector in South and South-East Asian lower-middle-income countries and was sense-checked with recycling sector stakeholders. Landfilling and open dumping are based on the ecoinvent waste models, using Cambodia-specific climate and technology data. Open burning, incineration, high technology mechanical recycling and closed-loop rPET recycling are based on the ecoinvent datasets, adapted for the Cambodia context where relevant. RDF production is based on academically published life cycle data from Asian studies. Data for background processes - all those processes that provide materials and services into the foreground life cycle stages, including raw material production, electricity generation and transmission, road and sea transport, production of fuels, and water and waste treatment processes - are sourced from the ecoinvent database, adapted for the Cambodia context where relevant.

An important consideration in LCAs involving secondary products is how the benefits and burdens of producing secondary materials are allocated between the system producing them (i.e. plastic waste generated by individuals and businesses) and the product system that subsequently uses them (e.g. manufacturer utilizing recyclate to produce new plastic products). In this study, the ISO 14044 Standard recommendations are followed, meaning that **system expansion is deemed the most appropriate approach** for identifying the environmentally preferred end-of-life management option for plastic waste and is used in this LCA study to fully account for the benefits of sending plastic waste for recycling or energy recovery.

The LCA results demonstrate that diverting plastic waste from landfills, open dumps and, especially, open burning has substantial environmental benefits. By **avoiding disposal impacts and producing recyclate, which avoids the production of virgin plastic, all three recycling options considered significantly reduce the life cycle impacts of plastic waste management**. These lower impacts are seen across all life cycle environmental impact categories, including climate change, human health, ecosystem quality and non-renewable resource depletion impacts. Alongside this, the recycling options align with **circular-economy principals** and ensure the value of plastics are not lost from the economy, as well as ensuring **less plastic enters the nature environment and water systems**. The LCA findings are robust with respect to transport distances, polymers recycled, the quality of recyclate produced (quality ratios), recycling energy inputs and recycling yields, as well as the allocation approach followed (cut-off, CFF or system expansion). Nonetheless, end-of-life allocation does affect the extent of the reduction in environmental impacts relative to the baseline scenario.

In cases where **plastics cannot be recycled** currently (e.g. multilayers), the LCA demonstrates that **RDF production is the preferred management option**. RDF production has lower human health and ecosystem quality impacts, as well as non-renewable resource depletion impacts, than the baseline scenario, landfilling or incineration with energy recovery, although it has worse water scarcity impacts. The magnitude of reductions in human health and ecosystem quality impacts however indicates that RDF production is overall the preferrable option. The LCA results in this case are also robust in respect to allocation approach followed. The RDF production option however does not align with circular-economy principals, as the value of the plastic material is lost, although it ensures that **less plastic enters the nature environment and water systems.**

Although LCA results indicate that closed-loop recycling (i.e. production on high quality HDPE/PP/LDPE and food-grade rPET recyclate) is the environmentally preferable option, these results are not judged to be robust within the data limitations of the study. The high technology and closed-loop recycling options have higher recycling processing impacts than low-technology recycling, as practiced by SMEs in Cambodia, due to increased energy, material and water inputs for processing. However, the higher technology systems produce better quality recyclate and therefore offset an increased amount of virgin plastic production, resulting in greater avoided impacts. The differential between these two (i.e. the net impacts) depends on recycling energy inputs, recycling yields and the quality of output recyclate and therefore results are not definitive on which option is preferable.

In order to improve the life cycle environmental sustainability of recycling operations, it is key to **improve the quality (especially cleanliness) of incoming plastic waste, minimise energy consumption and reduce chemical consumption**. Improved plastic waste quality has numerous knock-on impacts, including reducing the water and chemicals required for cleaning, reducing the amount of waste generated from processing and improving the quality of output recyclate. If energy consumption cannot be reduced, it is also possible to mitigate impacts by switching to cleaner energy sources (e.g. natural gas over diesel) or preferably renewable energy sources.

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1 Introduction

Globally plastics are experiencing unprecedented scrutiny from consumers and governments alike amid growing concerns of the viability of their production from fossil fuel resources and impact of improperly managed plastic waste on human health and the health of our environment. Despite this, plastic plays a vital role in many sectors and has been shown by numerous life cycle assessment (LCA) studies to be the preferred material for products such as food packaging. There is therefore the need to improve plastic waste management systems and improve plastic circularity to ensure that plastic can still play a vital role in human's day-to-day lives, without compromising non-renewable resources or the health of humans and the environment.

The International Environmental Technology Centre (IETC), a division of UNEP's Industry and Economy Division, works with developing countries on sustainable solutions for environmental challenges and has a particular focus on holistic waste management. In line with this mandate and the global plastics waste challenge, UNEP-IETC has implemented projects across Asia, including in Cambodia and Pakistan, to advance plastic waste management. These projects focus on empowering small and medium enterprises (SMEs) working in plastics recycling to implement sound, sustainable recycling technologies, while ensuring entrepreneurship and innovation within the circular economy.

There is therefore the need to fully understand the recycling technologies being implemented by SMEs, or potentially being implemented by SMEs, to ensure that the recycling technologies and methods employed are environmentally sustainable and align with circular economy principals, while providing economic and social stability for the SMEs and their employees. UNEP-IETC have therefore commissioned this life cycle assessment (LCA) study on plastic recycling technologies and other plastic end-of-life options. The LCA assesses the effectiveness and life cycle environmental impacts of the different management options to help identify sustainable recycling options for SMEs, as well as how the sustainability can be improved over time.

This study is a gate-to-grave LCA and focusses only on the end-of-life management of plastic waste. The report is laid out according to the stages of an ISO-compliant LCA study[1] (goal and scope definition, inventory analysis, impact assessment and interpretation), following a short introduction to life cycle assessment. The section on goal and scope definition lays out the main methodological considerations of the LCA, whilst the inventory analysis section details the life cycle models, particularly the data sources used to construct the life cycle models. Following this, the impact assessment section provides details on the environmental metrics used in the analysis. Life cycle interpretation presents the results and insights to be gained from the LCA, including the highlighting of sustainability of various plastic management options and key life cycle stages that can be targeted to improve sustainability. The report concludes with the main messages and recommendations for all recycling value chain stakeholders, including funders, policy makers, SME recyclers and UNEP teams.

1.1 Life cycle assessment (LCA)

LCA provides a structured framework in which to model the consequences that a product (or service) has on the natural environment and society. In an LCA, all stages in the life cycle of the product are considered, from the mining, extraction or growing of its raw materials, through its manufacturing, distribution and use, right to the final disposal of its components. Raw materials and emissions are not only considered for the product under study, but also for all the other materials used in the life cycle of the product (e.g. electricity, packaging, transportation). Together all these stages - and the unit processes they are comprised of - make up the life cycle of the product, as

[1] ISO 14044:2006 *Environmental management – Life cycle assessment – Requirements and guidelines*, International Organization for Standardization, Geneva, Switzerland.

shown in Figure 1. The term value chain, defined as the set of activities that businesses operating within a specific product system perform to deliver a good or service to the market, denotes a similar concept.

The first stage of an LCA is Goal and Scope definition, in which the intended use of the study is clearly defined, together with what this means for the various methodological choices needing to be made, for example, the definition of the system boundary2. All raw materials and emissions (inputs and outputs) are considered for each of the processes included in the system boundary. Inputs include the use of natural resources, such as land and water, as well as manufactured materials, such as fuels, chemicals etc. Outputs are the releases to air, water and soil, as well as all products and by-products. The outcome of the second stage of an LCA study (Inventory Analysis) is thus a long list of resources and emissions (input and outputs) associated with delivering a particular product's function, termed the life cycle inventory (LCI).

The subsequent stage of LCA (Life Cycle Impact Assessment) enables the interpretation of this long list of inputs and outputs by connecting them to their corresponding environmental impacts. In this way, the inputs and outputs are summed up into common areas of environmental concern (e.g. impacts on human health, impacts on ecosystems, non-renewable resource depletion). This can be done at varying degrees of complexity, and a number of different life cycle impact assessment (LCIA) methods have been developed to quantify the potential environmental impacts of a product system. The final stage of LCA is Interpretation, in which the results are analyzed and the outcomes presented.

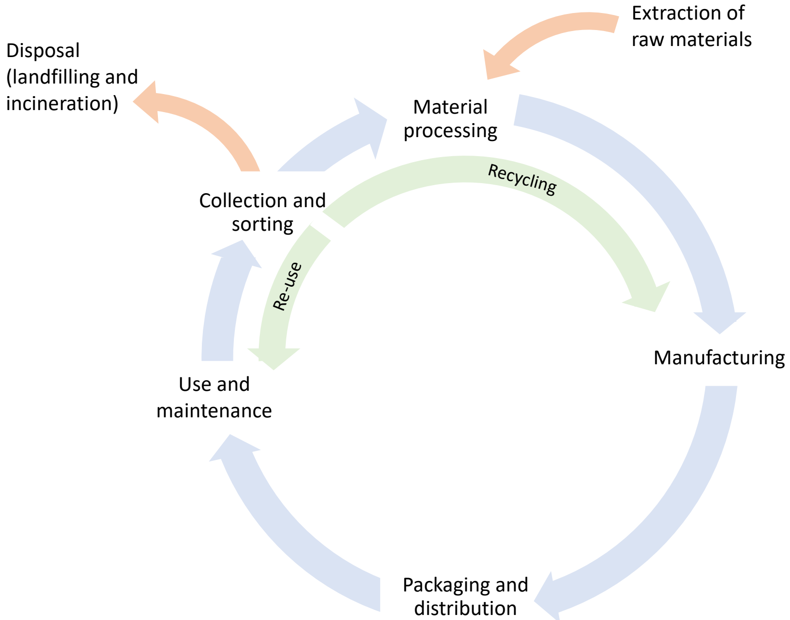

Figure 1: Representation of a product life cycle

An LCA is an inherently complex and data intensive undertaking and, as with any model, involves a simplification of reality. However, the ambitious undertaking of analysing product systems with LCA is driven by its benefits, which include:

- Creating awareness that decisions are not isolated, but that they influence a larger system;
- Promoting decision-making for the longer term, by considering all environmental and socio-economic issues and potential knock-on effects associated with a decision choice; and
- Improving entire systems and not just single parts of systems, by avoiding decisions that fix one problem but cause another unexpected problem (like mitigating air pollution but increasing water pollution).

[2] The system boundary encompasses all the processes that make up the life cycle of the product to be analyzed.

Impact assessment (LCIA) predicts potential environmental impacts or damages. Life cycle inventory data typically span multiple geographical locations across countries and continents in today's global supply chains. LCIA's predictive models are therefore not like environmental impact assessment (EIA) models that accurately characterise the actual risks associated with emissions at a particular location. Indeed, the value of an LCA study lies not so much with the final numbers, but rather with the exploration and consequent understanding of the product system it assesses.

Especially valuable is LCA's ability to highlight hotspots along the value chain, that is, to show the areas of highest potential impact, and also to highlight trade-offs between different impacts. It is seldom that one system or decision option performs better than another in all aspects of environmental impacts. Thus, understanding these trade-offs is a prerequisite towards improving the sustainability of product systems.

2 Goal and scope definition

The international standard on life cycle assessment, ISO 14044:2006, requires that the items in the following sub-sections be considered and clearly described when defining the goal and scope of an LCA study.

2.1 Goal of the study

As per ISO 14044:2006, the goal of the study is defined through consideration of the following:

- The **intended application** is to support UNEP-IETC in their Asian SME plastic recycling project implementation, within Cambodia, by quantifying the environmental impacts of various recycling technologies and other plastic end-of-life management options. This understanding of the life cycle environmental impacts of different plastic waste management options will provide evidence of which technologies are environmentally sustainable and align with circular economy principles. Alongside this, it will provide an understanding of the environmental strengths and weaknesses of the different technologies and identify how weaknesses in each technology can be addressed. The later support will include identifying the environmental impact "hotspots" within each technology's value chain, along with, where possible, providing recommendations on how these "hotspots" can be reduced by SMEs and other recycling stakeholders.
- The **reason for carrying out the study** is to obtain a quantitative comparison of the life cycle environmental impacts of various plastic recycling technologies and other plastic end-of-life management options in the Cambodian (Asian lower-middle-income country) context. The evidence-based findings will assist the UNEP-IETC teams and SME recycling sector stakeholders to identify sustainable, circular recycling technologies and how these technologies can be improved going forward, while also providing guidance to policymakers and investors on how best to promote and support sustainable plastic waste management practices.
- The **intended audience** includes the UNEP-IETC team, as well as SME recycling practitioners, broader recycling sector stakeholders, policymakers and impact investors. More detailed, recycling technology-specific results are primarily aimed at the UNEP-IETC and SME stakeholders, to assist them in identifying the most sustainable technology and operational choices, while broader results are aimed at other stakeholders to increase awareness and assist them with policy making and investment decisions.

The goal of the study is thus to quantify the life cycle environmental impacts of plastic recycling technologies and other plastic waste management options in Cambodia, with the view of identifying sustainable technologies available to SMEs and how best to improve sustainability going forward. A further goal is increased knowledge, allowing for evidence-based policy and investment decision-making to promote sustainable plastic recycling practices.

2.2 Scope of the study

The scope of the study covers decisions relating to the detail and accuracy of the study and related methodological decisions, including the choice of functional unit, system boundaries and data requirements.

2.2.1 The product system and functional unit

The **product system analysed is the end-of-life management of plastic waste in Cambodia and thus covers everything required to manage and/or treat this waste** (i.e., dispose of the waste or process it to a usable material).

The end-of-life management options covered by the study are:

- Status-quo plastic waste management (i.e. current split between open burning, dumping, landfilling, incineration, recycling etc.)
- Controlled landfilling
- Incineration with energy recovery (i.e. energy recovery in the form of electricity)
- Production of refuse derived fuel (RDF) (i.e. energy recovery in the form of fuel)
- Mechanical recycling
    - Current low-technology mechanical recycling employed by SMEs
    - Higher-technology open-loop mechanical recycling[3]
    - Closed-loop mechanical recycling of PET[4]

Based on both secondary data (Arshad, M and Rashid, F, 2020; Asian Development Bank, 2022; Hashmi et al., 2023; Majeed et al., 2018; Nawaz et al., 2021) and consultation with stakeholders in Cambodia, other forms of closed-loop mechanical recycling (e.g. food-grade rHDPE), chemical recycling (gasification, pyrolysis or thermal depolymerisation), dissolution recycling and biological (organic) recycling are not viable in Cambodia, due to economic and technological challenges, as well as a lack of bio-plastic consumption. This situation is commonplace throughout the world, with almost all plastic recycling currently occurring via mechanical routes and the vast majority of recyclers operating open-loop recycling plans, producing lower grade recyclates. PET is the one exception, with numerous closed-loop recycling plants operating worldwide producing food-grade rPET (Kalauni et al., 2025; Schwarz et al., 2021; Schyns and Shaver, 2021).

Due to project time constraints, as well as a lack of both primary and secondary data at a polymer-specific level, the product system is investigated for two scenarios, namely:

- **Recyclable plastics**, which primarily consist of PET and HDPE, along with certain types of PP and LDPE
- **Non-recyclable plastics**, which consist of PVC, PS, other polymers and mixed plastics (e.g. multi-layer laminates)

The functional unit, which is the product or service unit against which environmental impacts are measured, is chosen as **1,000 kg of plastic waste managed at end-of-life**.

2.2.2 The system boundary

The life cycle system is made up of all the life cycle stages (unit processes) making up the product system, enclosed by the system boundary. In this study, the **system boundary starts at plastic waste generation**, consistent with the scope of a **"gate-to-grave"** LCA investigation. Therefore, the **life cycle system includes waste collection;**

[3] Recycling that produces a recyclate of lower quality than the original polymer, resulting in the recyclate being utilized for a different application than the original, virgin polymer. Examples include bottle-to-fiber recycling.

[4] Recycling that produces recyclate that has the same quality and properties as the original polymer, meaning that the recyclate can be utilized for the same applications as the original, virgin polymer.

waste transportation; waste sorting; waste pre-processing; and end-of-life processing (recycling or disposal). Where appropriate, the **avoided processes** (virgin plastic production, electricity generation etc.) are included, as presented in Figure 2. The end-of-life processing (recycling or disposal) phase has the highest associated inputs and impacts and therefore was the key focus of data collection efforts.

The life cycle system considers plastic end-of-life and therefore does not include plastic production, distribution or use (i.e. prior to plastic waste generation), consistent with the "gate-to-grave" scope of this LCA. "Gate-to-grave" investigations are commonly used to evaluate end-of-life management options and as such will enhance understanding of the best plastic end-of-life management technologies to utilise in the Cambodian context.

The life cycle inventory models include all major material and energy inputs to the processes, as well as the emissions and wastes generated. Details on the life cycle models are given in Section 3.1.

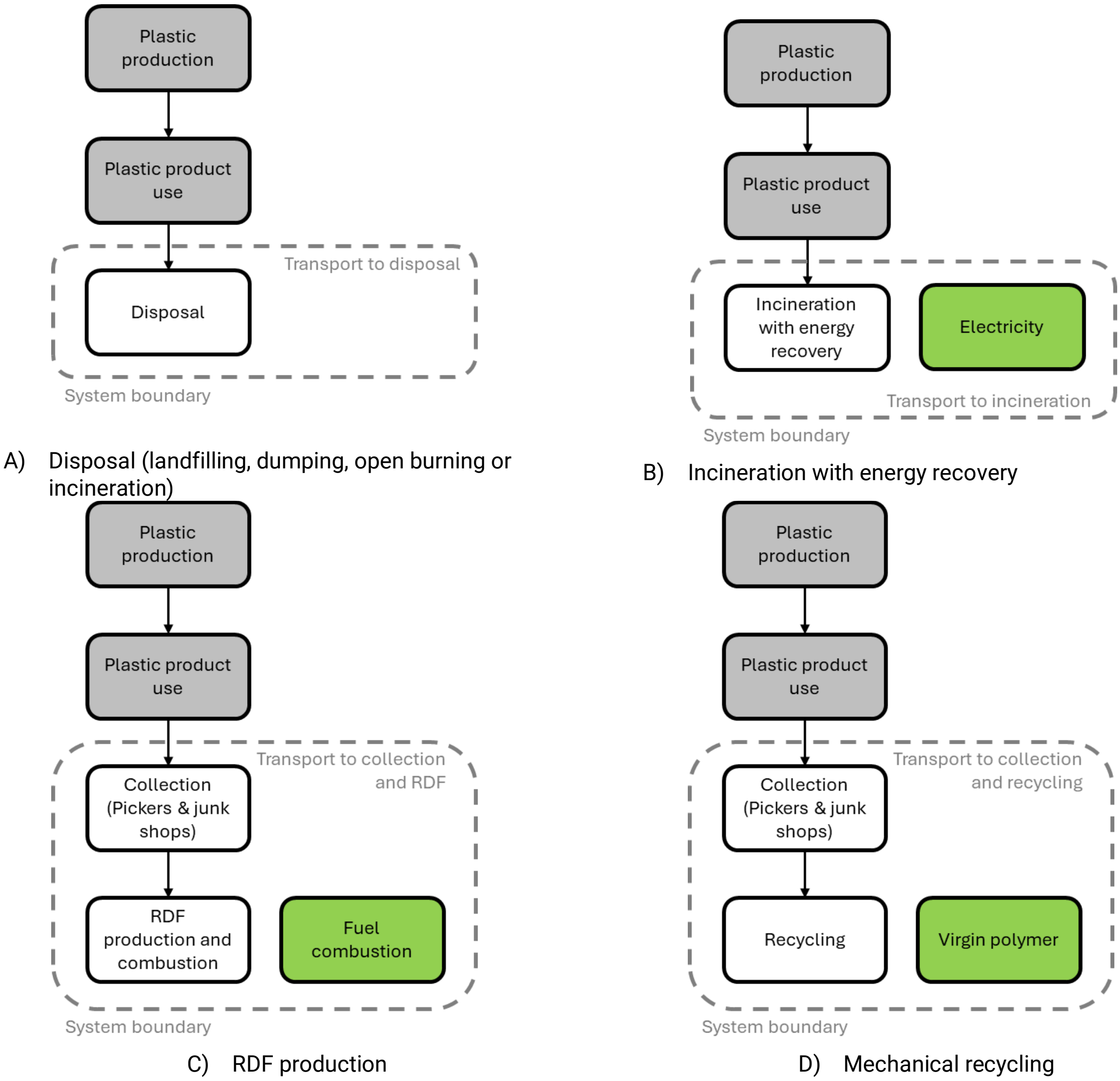

Figure 2: Simplified representation of the plastic end-of-life product systems considered in the study. Blocks shaded grey represent excluded life cycle stages, consistent with "gate-to-grave" LCA studies. Blocks shaded green represented avoided processes.

2.2.3 Allocation

Joint production allocation

Allocation is encountered in life cycle models when the **inputs and emissions of a process need to be apportioned between multiple products or services**. In the plastic waste management system, allocation is encountered in transport of plastic waste, where multiple materials may be transported in the same vehicle, and in upstream production (e.g. production of fuels at refineries), where inputs and emissions are available for the facility but not for one product specifically.

The stepwise approach recommended by ISO14040:2006 is followed for allocation between multiple products. That is, in cases where allocation cannot be avoided (e.g. by modelling the system in more detail), allocation is applied on the most relevant physical basis (e.g. volume or mass) or on a monetary basis (e.g. revenue).

No primary data collected within the study needed to be allocated and therefore for all background processes, joint production allocation utilises the allocation approaches followed by the ecoinvent database. As such, transport is allocated on a tonne.kilometers (i.e. with mass the physical load-limiting factor) basis, whilst fuel distillation is allocated on a mixture of energy, exergy and mass basis.

End-of-life allocation

The other place where allocation arises is at end-of-life where the benefits (and the burdens) of any secondary materials produced need to be allocated between the system producing them and the product system that subsequently uses them. This is a critical consideration in modelling end-of-life where useful products, such as recyclate or energy, are produced. This has been the topic of many reports, standards, guidelines and articles, with newer crediting methodologies being developed on an ongoing basis (e.g. Circular Footprint Formula (CFF) developed as part of the European Union's Environmental Footprint project during the late 2010s), with all methodologies having positive and negatives and generally favouring either the suppliers of material for recycling or the users of recycled materials. It is for this reason that the **ISO 14044:2006 Standard recommends that allocation is avoided wherever possible, through methods such as system expansion**. System expansion avoids allocation choices, which can significantly alter LCA results, and is relatively easy to understand for non-LCA experts, unlike methodologies such as the CFF.

For these reasons, and in line with ISO 14044:2006, **system expansion is applied in the study, whereby the waste system is credited for avoided production** (e.g. production of recyclate credited for avoiding the production of virgin plastic). System expansion also identifies the end-of-life option that brings the most environmental benefits, thus matching the goal of this study.

A critical consideration when applying system expansion/avoided production is determining the type and quantity of displaced material or energy. This requires an understanding of markets, as this can be context- and location-specific (e.g. energy produced from incineration may offset grid electricity or boilers). "Downcycling" is also an issue with system expansion/avoided production, as the displacement may not be 1:1. Whilst fuel replacements can be done on calorific value, material replacements are typically less straightforward. For example, 1 kg recycled plastic is not likely to replace 1 kg virgin plastic as there will be some loss in polymer quality over the recycling process and therefore manufacturing losses are higher.

For this reason, replacement factors (quality ratios) are carefully considered and investigated within this study (see Section 3.1) to ensure that results are not bias towards either recyclers or virgin plastic producers.

2.2.4 Impact categories selected and methodology of impact assessment

The IMPACT World+ impact assessment method, developed by the International Reference Centre for Life Cycle Assessment and Sustainable Transition (CIRAIG) and the Technical University of Denmark (DTU), is applied in this study[5]. IMPACT World+ is the result of an update of three existing, well recognised LCA methods, namely: IMPACT 2002+, EDIP and LUCAS.

Details on the method are given in Section 3.2, with an overview of the impact categories given in Table 14 and Figure 3. To simplify analysis and interpretation of results, the following disaggregated and partially aggregated impact categories are reported in this study:

- Climate change (both short-term and long-term, with a focus on short-term)
- Water scarcity
- Human health AoP
- Ecosystem quality AoP
- Fossil and nuclear energy use

The human health and ecosystem quality AoPs can also be summed into an aggregated "single-score" impact; however, this is used sparingly in reporting as it does not consider the impacts of non-renewable resource depletion.

Alongside these life cycle environmental impact categories, the following factors are reported in this study:

- Plastic footprint
- Material Circularity Indicator (MCI)

2.2.5 Data requirements

All LCAs utilise a blend of primary (data collected specifically for the project) and secondary (data sourced from life cycle databases and literature) data to model the life cycle systems within the system boundaries. Ideally, models are constructed using as much primary data as possible, especially for key life cycle stages such as recycling processing in this study. However, the amount of primary data collected is generally limited by the project timelines, how much control stakeholders have over the value chain (e.g. do stakeholders have knowledge of where materials are sourced from and the upstream production routes) and the data records maintained by stakeholders (e.g. do stakeholders maintain records of their annual purchases).

In this study primary data collection was limited by both project time limitations and the scarcity of primary data available from recycling sector stakeholders. These limitations are commonplace in the waste sector, especially in developing countries, and amongst SMEs, especially SMEs operating within the informal economy. Due to the informal nature of these market spaces typically data simply does not exist, as very little data is documented, recorded or regulated. This is further compounded by the number of role players operating in the space, often utilising vastly different collection and/or processing methods, which cannot be effectively covered by surveys within a short project period. Additional challenges for primary data collection arise due to recycling markets being fluid, meaning that operations and data are highly dynamic depending on current market conditions and prices, resulting in data becoming out-of-date within a short space of time.

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[5] Initially it was planned to apply the Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM) method. The GLAM impact assessment methodology is chosen because its multi-year development involved the collaboration of hundreds of experts from across the LCA space, including LCIA developers, LCA practitioners and users of LCA results, with the aim of developing a global consensus methodology. However, although the characterization factors for GLAM were published at the end of 2024, the methodology has not yet been implemented in SimaPro or other LCA software and the normalization factors are yet to be published (finalization and publishing expected Q1 2025).

For this reason, primary data collection focussed only on the three key value chain stages for a recycling "gate-to-grave" LCA, namely: plastic waste collection, plastic waste pre-processing, and plastic recycling. The data collection also focussed exclusively on SME recyclers, who are undertaking low-technology mechanical recycling.

A hybrid approach was utilised where applicable secondary data was collected on these life cycle stages in order to build base knowledge of the recycling value chain and value chain inputs within Cambodia. This secondary data allowed for the determination of key data points that would be the focus of primary data collection, as well providing data that was used for the LCA modelling wherever primary data was unavailable or could not be collected. The primary data collection process also utilised the secondary data as a discussion point for stakeholders, allowing them to provide feedback on whether the secondary data accurately reflected the Cambodian situation (i.e. more qualitative information than quantitative data). This process provided sense-checking of the secondary data, as well as offered guidance on which secondary data sources were relevant within the study boundaries.

Primary data was collected from twelve (12) SME recyclers in Cambodia. This primary data collection focused on understanding the recycling value chain dynamics (i.e. where and how plastic waste is collected and the method of further cleaning, sorting and recycling), as well as the plastic recycling (processing) stage as this is the most relevant life cycle stage within the system boundaries. Specific data inputs sought from the stakeholders focuses on the most relevant processes and variables, as summarised in Table 1.

Table 1: Most relevant processes and variables for SME plastic recycling in Cambodia

Process or variable	Comment and units
Plastic polymers recycled	Share of each polymer type (PET, HDPE etc.) processed
Plastic recycling yield	Recyclate output per tonne of input (tonne/ tonne input), to understand process losses and resulting waste outputs to disposal
Electricity consumption	Electrical energy inputs for processing (kWh/tonne input)
Fuel consumption	Fuel energy inputs, disaggregated by fuel type, for processing (L/tonne input or MJ/tonne input)
Water consumption	Water inputs for cleaning and processing (L/tonne input)
Chemical consumption	Chemical inputs, disaggregated by type, for cleaning and processing (kg/tonne input)
Plastic recyclate quality	Overall quality of recyclate, which is indicated by the end-use for recyclate sold. This impacts the recycling quality ratio applicable for the recyclate (Table 12) and therefore the amount of virgin plastic offset. Although it is not possible to determine a definitive value for the recycling quality ratio, understanding the end-use of the recyclate sold provides insights into whether the recyclate is used for lower quality (quality ratio around 75%), higher quality (quality ratio around 90%) or food-grade (quality ratio around 100%) applications

Data on alternative end-of-life processes are sourced from secondary data sources, as summarised below:

- Landfilling — Doka LCA model, as utilised by ecoinvent
- Open dumping — Doka LCA model, as utilised by ecoinvent
- Open burning — ecoinvent (based on Doka LCA model)
- Incineration — ecoinvent (based on Doka LCA model)
- Incineration with energy recovery — ecoinvent (based on Doka LCA model)
- RDF production — Literature (journal articles)
- Higher technology open-loop recycling — ecoinvent
- Closed-loop PET recycling — ecoinvent

Background processes are all those processes that provide materials and services into the foreground life cycle stages, including raw material production, electricity generation and transmission, road and sea transport, production of fuels, production of chemicals, and water and waste treatment processes. Data for background processes are sourced from the ecoinvent database (cut-off system model), adapted for Cambodia and other geographical contexts, where relevant.

Details on the data sources and datasets used in the life cycle models are provided in Section 3.1.

2.2.6 Assumptions and limitations

As with all life cycle models, a large number of assumptions are made when developing the models. The life cycle models are explained in Section 3.1, along with any assumptions made when constructing them.

LCA results are inherently limited by the quality of the data used to construct them. The considerable number of LCI datasets required to complete any LCA model means that simplifications and the use of proxy datasets are inevitable to some degree. This LCA is no different, with data quality considerations with respect to the quality of the results discussed in Section 4.3.

The key data-related limitations are linked to the use of predominantly secondary data within the LCA modelling. Although the key secondary data on SME's recycling value chain and operations was cross-checked with recycling stakeholders and supplemented with primary data wherever possible, there is still a large degree of uncertainty associated with this data. To determine the effect of this uncertainty, and to test the validity of results, key data points were tested using sensitivity analyses.

3 The life cycle model

3.1 Inventory analysis

The following sub-sections provide details on the gate-to-grave life cycle models developed for Cambodian plastic waste management system. Unless otherwise noted, ecoinvent datasets applying the cut-off system model are used in the life cycle models.

3.1.1 Baseline scenario

In order to assess the environmental impact benefits and disadvantages of recycling, as well as other plastic waste management methods, it is key to understand how plastic waste is currently managed, or unmanaged, within Cambodia. This management split is summarised in Table 2 and includes waste that is formally collected (57%) and left uncollected (43%) (Pheakdey et al., 2022; Vimeanreaksmey, D, 2022).

Landfilling within Cambodia is in uncontrolled (unsanitary) landfill sites, without any technologies such as landfill gas capture or cell compaction (iDE, 2024; Pheakdey et al., 2022; Vimeanreaksmey, D, 2022). Currently recycling is mostly undertaken by SME recyclers, utilising low-technology mechanical recycling processes, or through the export of waste to international recyclers (CSARO, 1997; iDE, 2024; Jeronimo, M, 2020; Pheakdey et al., 2022; UNEP et al., 2018; Vimeanreaksmey, D, 2022). Recent trade data shows that around 14% of collected plastic waste is exported to international recyclers (ITC, 2025; Pheakdey et al., 2022).

Table 2: Current plastic waste end-of-life management split in Cambodia

End-of-life management	Share	Reference
Landfilling	47%	(Pheakdey et al., 2022; Vimeanreaksmey, D, 2022)
Incineration	4%	(Pheakdey et al., 2022; Vimeanreaksmey, D, 2022)
Open dumping	17%	(Pheakdey et al., 2022)
Open burning	23%	(Pheakdey et al., 2022)
Recycling	9%	(Pheakdey et al., 2022; World Bank, 2024)
TOTAL	100%	

Each of these end-of-life management methods are modelled using the inventories and data presented below according to technology type.

3.1.2 Landfilling

As mentioned above, landfilling in Cambodia is limited to unsanitary landfill sites without higher-technology mitigation features, such as leachate capture and methane recovery systems. In order to accurately represent Cambodian unsanitary landfill sites, the waste model developed by ecoinvent (Doka, G, 2021) was contextualised using Cambodia climatic and waste management data. The climatic parameters able to be input into the landfill spreadsheet model are shown in Table 3 (i.e. inputted into the Doka spreadsheet model, with the inventory inputs and outputs then imported into SimaPro). Unsanitary landfill sites are modelled with no leachate collection or treatment, as well as without landfill gas capture. Plastic composition is based on the default mixed plastic composition within the Doka model.

Table 3: Key climatic value for landfill modelling

Climatic variable	Value	Reference
Evapotranspiration rate	1,138 mm/year	(NASA AppEEARS, 2025)
Precipitation	1,888 mm/year	(CRU Data, 2024)
Mean temperature	27.5 °C	(CRU Data, 2024)

Waste is assumed to be transported an average distance of 24 kilometres to landfill (Aryan et al., 2019; Majeed et al., 2018; PLACES, 2023). The datasets applied to model the inputs into this waste transportation are listed in Table 4.

Table 4: Inventory inputs into waste transportation to landfill [per kilogram plastic waste]

Inputs: Materials & fuels	ecoinvent dataset used / Geography	Value	Reference
Road	Road / Global	1.55E-5 my	ecoinvent dataset (*Municipal waste collection service by 21 metric ton lorry / Global*)
Waste collection vehicle	Waste collection lorry, 21 metric ton / Global	1.10E-8 units	ecoinvent dataset (*Municipal waste collection service by 21 metric ton lorry / Global*)
Inputs: Electricity & heat	**ecoinvent dataset used / Geography**	**Value**	**Reference**
Diesel	Diesel, burned in building machine / Global	6.64E-2 MJ	(Aryan et al., 2019; Majeed et al., 2018)

3.1.3 Open dumping

As with unsanitary landfill disposal, in order to accurately represent Cambodian open dumping, the waste model developed by ecoinvent (Doka, G, 2021) was contextualised using Cambodia climatic and waste management data. The climatic parameters able to be input into the landfill spreadsheet model are shown in Table 3 (i.e. inputted into the Doka spreadsheet model, with the inventory inputs and outputs then imported into SimaPro). Plastic composition is based on the default mixed plastic composition within the Doka model.

It is assumed there is no transportation for dumped waste.

3.1.4 Open burning

The burning dataset in ecoinvent (*Treatment of waste plastic, mixture, open burning / Global*) was adapted to the Cambodian geographical context. This adaption involved changing relevant emissions to air (nitrogen dioxide, nitrogen oxides, sulphur dioxide and water) to the Cambodia-linked emission (e.g. *Water / Global* to *Water / Cambodia*).

It is assumed there is no transportation for openly burnt waste.

3.1.5 Incineration

The incineration dataset in ecoinvent (*Treatment of waste plastic, mixture, municipal incineration / Global*) was adapted to the Cambodian geographical context. This adaption involved changing relevant material inputs (ammonia and decarbonised water), emissions to air (ammonia, nitrogen dioxide, nitrogen oxides, NMVOC, sulphur dioxide and water) and emissions to water (BOD, COD, nitrates and water) to the Cambodia-linked emission (e.g. *Water / Global* to *Water / Cambodia*).

Waste is assumed to be transported an average distance of 51 kilometres to incineration (Aryan et al., 2019; Majeed et al., 2018; PLACES, 2023). The datasets applied to model the inputs into this waste transportation are listed in Table 5.

Table 5: Inventory inputs into waste transportation to incineration [per kilogram plastic waste]

Inputs: Materials & fuels	ecoinvent dataset used / Geography	Value	Reference
Road	Road / Global	3.29E-5 my	ecoinvent dataset (*Municipal waste collection service by 21 metric ton lorry / Global*)
Waste collection vehicle	Waste collection lorry, 21 metric ton / Global	2.32E-8 units	ecoinvent dataset (*Municipal waste collection service by 21 metric ton lorry / Global*)
Inputs: Electricity & heat	**ecoinvent dataset used / Geography**	**Value**	**Reference**
Diesel	Diesel, burned in building machine / Global	1.70E-1 MJ	(Aryan et al., 2019; Majeed et al., 2018)

Avoided processes according to system expansion: In the case of incineration with energy recovery, the energy recovery process generates electricity, which offsets Cambodian grid electricity. It is assumed that 3.93 MJ of electricity are produced per kilogram of plastic incinerated (*Treatment of waste plastic, mixture, municipal incineration / Global*), with the avoided electricity represented by the Cambodia electricity ecoinvent dataset (*Electricity, low voltage, market for / Cambodia*).

3.1.6 RDF production

Refuse derived fuel (RDF) is produced and used in Asian cement kilns to replace traditional fossil fuels (Syeda et al., 2017), although it could also be utilised in other industrial operations where energy is produced onsite from fossil fuels (Salaripoor et al., 2025).

As the potential users of RDF are limited, waste is assumed to be transported an average distance of 300 kilometres to RDF production and combustion (Syeda et al., 2017). The datasets applied to model the inputs into this waste transportation are listed in Table 10.

Table 6: Inventory inputs into waste transportation to RDF production [per kilogram plastic waste]

Inputs: Materials & fuels	ecoinvent dataset used / Geography	Value	Reference
Road	Road / Global	1.92E-4 my	ecoinvent dataset (*Municipal waste collection service by 21 metric ton lorry / Global*)
Waste collection vehicle	Waste collection lorry, 21 metric ton / Global	1.36E-7 units	ecoinvent dataset (*Municipal waste collection service by 21 metric ton lorry / Global*)
Inputs: Electricity & heat	**ecoinvent dataset used / Geography**	**Value**	**Reference**
Diesel	Diesel, burned in building machine / Global	9.95E-1 MJ	(Aryan et al., 2019; Majeed et al., 2018)

RDF production requires electricity for site operations, including screening, shredding and grinding; however, for non-organic waste streams, such as plastic waste where drying is not required, the electricity required is minimal. The datasets applied to model the inputs into RDF production are listed in Table 7, which produces 0.92 kilograms of RDF per kilogram of plastic waste.

Table 7: Inventory inputs into RDF production [per kilogram plastic waste]

Inputs: Materials & fuels	ecoinvent dataset used / Geography	Value	Reference
Infrastructure	Waste preparation facility, no machinery / Global (*adapted from Global waste preparation facility dataset)*	2.00E-9 units	ecoinvent dataset (*Waste preparation facility / Global*)
Inputs: Electricity & heat	**ecoinvent dataset used / Geography**	**Value**	**Reference**
Electricity	Electricity, low voltage, market for / Cambodia	3.15E-1 kWh	(Ming-Hui, X. et al., 2010; Salaripoor et al., 2025)
Outputs: Waste treatment	**ecoinvent dataset used / Geography**	**Value**	**Reference**
Waste to landfill	Municipal solid waste, treatment of municipal solid waste, unsanitary landfill, very wet infiltration class (1000mm) / Global	0.073 kg	(Ming-Hui, X. et al., 2010) – Split between disposal types based on national waste management data (Table 2)
Waste to incineration	Municipal solid waste, treatment of municipal solid waste, municipal incineration / Global	0.007 kg	

Avoided processes according to system expansion: The RDF produced is combusted as an energy source, which offsets the combustion of fossil fuels. Based on the calorific value of plastic waste, each kilogram of RDF produced offsets 34.5 MJ of fossil fuels (Ming-Hui, X. et al., 2010; Salaripoor et al., 2025). RDF combustion emissions are based on plastic incineration (see Section 3.1.5), while the split between the fossil fuels replaced is based on the Cambodia energy mix (IEA, 2025). The datasets applied to model RDF combustion and avoided fossil fuel combustion are listed in Table 8.

Table 8: Inventory inputs into RDF combustion and resulting avoided fossil fuel combustion [per kilogram plastic waste]

Outputs: Avoided products	ecoinvent dataset used / Geography	Value	Reference
Avoided coal	Heat, district or industrial, other than natural gas, heat production, at hard coal industrial furnace 1-10MW / Global	9.23 MJ	(Ming-Hui, X. et al., 2010; Salaripoor et al., 2025; IEA, 2025)
Avoided oil	Heat, district or industrial, other than natural gas, heavy fuel oil, at industrial furnace 1MW / Global	22.47 MJ	
Avoided natural gas	Heat, district or industrial, natural gas / Global	0 MJ	
Outputs: Waste treatment	**ecoinvent dataset used / Geography**	**Value**	**Reference**
Plastic RDF combustion	Treatment of waste plastic, mixture, municipal incineration / Cambodia (*adapted from Global dataset)*	0.92 kg	(Ming-Hui, X. et al., 2010; Salaripoor et al., 2025)

3.1.7 SME plastic recycling

The recycling industry in Cambodia is still predominantly informal, with the value chain predominantly being undertaken by individuals or small businesses. This value chain includes the following stages (CSARO, 1997; Hibino et al., 2024; iDE, 2024; Jeronimo, M, 2020; Pheakdey et al., 2022; PLACES, 2023; Seng et al., 2018; UNEP et al., 2018; Vimeanreaksmey, D, 2022), as confirmed with SME recyclers within Cambodia:

- **Informal collection**: Plastic waste is collected by waste buyers and pickers directly from households, rubbish bins, transfer points, and landfills/dumps, as well as industrial sources (post-industrial/pre-consumer plastic)
    - Waste buyers purchase valuable plastic items, such as PET bottles, directly from households, businesses and industries, who separate them from their general waste stream to obtain the small collection fee. Although this collection is source separated, the plastic waste collected is not necessarily clean, especially in the case of household and commercial waste, and is combined with dirty plastic from other sources. Some recyclers favour purchasing this source separated, cleaner waste, although overall nationwide statistics show that only 40% of plastic is collected via purchases from households, businesses and industrial sources.
    - Waste pickers collected valuable plastic items from bins, transfer points, landfills, dumps and any other source. As this plastic is collected from the general waste stream, the plastic is dirty and is commonly soiled with organic matter. It is estimated that 60% of plastic is collected directly from the waste stream.
    - Transportation to buyers is via foot, bicycle or other forms of non-mechanical transportation.
- **Junkshops and middlemen**: Waste buyers and pickers sell their collected plastic to middlemen, who then sell the plastic to junkshops, or directly to junkshops. Commonly the plastic waste will go through various middlemen and junkshops before landing at larger junkshops where the plastic is sorted by polymer type for recyclers. This sorting is typically manual, without the use of machinery to improve the sorting efficiency[6]. However, machinery may be used to shred plastic items or compress the plastic into bales.
    - Following sorting, and potential shredding and/or baling, the plastic is either sold to Cambodian recyclers or exported to international recyclers, mainly within Asia.
    - Transportation to recyclers and international markets is via typically via road and/or sea transportation.
- **Recyclers**: Recycling is typically undertaken by small businesses, using mechanical recycling processes. Due to the expense of recycling machinery, the processing is kept as manual as possible (e.g. washing, sorting and shredding will be done by hand), with only low-technology inputs. The recycling process includes plastic washing and removal of unwanted materials; shredding; melting of the plastic; and pelletisation of the remelted polymer. Melting and pelletisation can occur manually (e.g. melting in a pan over an open flame before being manually poured into water to solidify) or through simple melting and pelletisation machinery. The simplicity of this recycling processes means that the recyclate produced is

[6] Consultation with recyclers revealed that certain recyclers utilize mechanical sorting. However, no information was collected from junkshops utilizing mechanical sorting.

not of virgin quality and it is therefore utilised for lower quality applications (i.e. open-loop recycling or "downcycling"). Examples of these lower quality applications includes plastic bricks and plastic furniture.

The Cambodian plastic recycling value chain therefore relies heavily on manual labour and is extremely low technology. This is different to the mechanical recycling value chains in most developed nations, and many developing nations, where mechanical recycling processes are highly mechanised and automated. Furthermore, the input plastic waste arriving dirty, unlike nations where "separation at source"[7] or "drop off"[8] collection programmes exist to collect clean plastic waste. For this reason, secondary data sources were carefully selected to ensure that they match the operations currently occurring in Cambodia (e.g. secondary data is based on low-technology mechanical recycling occurring in India and Pakistan, rather than high-technology, automated recycling occurring in Europe).

Collection and transport to middlemen/junkshops

Both informal collection and the transportation of the collected plastic waste to middlemen and junkshops is manual and therefore no inputs or emissions occur from these life cycle stages. As such, these life cycle stages are not modelled within the LCA.

Junkshops and transport to recyclers

Junkshop processing is also predominantly manual, although some electricity is utilised for the operation of facilities, including for lighting and the operation of any machinery. The datasets applied to model the inputs into these junkshops are listed in Table 9.

Table 9: Inventory inputs into junkshop operation [per kilogram plastic waste]

Inputs: Materials & fuels	ecoinvent dataset used / Geography	Value	Reference
Infrastructure	Waste preparation facility, no machinery / Global (*adapted from Global waste preparation facility dataset)*	2.00E-9 units	ecoinvent dataset (*Waste preparation facility / Global*)
Inputs: Electricity & heat	**ecoinvent dataset used / Geography**	**Value**	**Reference**
Electricity	Electricity, low voltage, market for / Cambodia	1.20E-3 kWh	(Aryan et al., 2019; Majeed et al., 2018)

For plastic recycled within Cambodia, it is assumed that the average transport distance between junkshops sorting the plastic and the recycler is 137 kilometres based on the weighted average of data from Cambodian recyclers (Minimum: 10 km; Maximum: 300 km). Secondary data suggested an average transport distance of 51 km (Aryan et al., 2019; Majeed et al., 2018; PLACES, 2023), which is within the range of recyclers interviewed although significantly lower than the average. The datasets applied to model the inputs into this waste transportation are listed in Table 10.

[7] Households and businesses collect recyclable waste, such as plastic, separately to their general waste stream to keep the recyclables clean. The separated recyclable waste is collected separately to the municipal soldi waste stream and delivered directly to processes and/or recyclers.
[8] Households collect recyclable waste, such as plastic, separately to their general waste stream to keep the recyclables clean. They then deliver the separated recyclable waste to centralised "drop off" (collection) centres.

Table 10: Inventory inputs into waste transportation to recyclers within Cambodia [per kilogram plastic waste]

Inputs: Materials & fuels	ecoinvent dataset used / Geography	Value	Reference
Road	Road / Global	8.81E-5 my	ecoinvent dataset (*Municipal waste collection service by 21 metric ton lorry / Global*)
Waste collection vehicle	Waste collection lorry, 21 metric ton / Global	6.21E-8 units	ecoinvent dataset (*Municipal waste collection service by 21 metric ton lorry / Global*)
Inputs: Electricity & heat	**ecoinvent dataset used / Geography**	**Value**	**Reference**
Diesel	Diesel, burned in building machine / Global	4.56E-1 MJ	(Aryan et al., 2019; Majeed et al., 2018)

For plastic exported outside of Cambodia, transportation is based on the distances to the two largest export markets for Cambodian plastic waste in 2023 (Malaysia: 72%, Taiwan: 26%, representing 98% of exports) (ITC, 2025). The transportation requirements are based on transfer of the plastic waste from the capital city (Phnom Penh) to the capital city of the relevant nation, via road (GoogleMaps) and sea (SeaDistance.org). The datasets applied to model the inputs into this waste transportation are listed in Table 11.

Table 11: Inventory inputs into waste export transportation to recyclers outside of Cambodia [per kilogram plastic waste]

Inputs: Materials & fuels	ecoinvent dataset used / Geography	Value	Reference
Road transport	Transport, freight, lorry, unspecified / Global	0.257 tonne.km	257 km based on weighted average of road transport to the two export nations (Phnom Penh to port and port to capital city centre; Taiwan)
Sea transport	Transport, freight, sea, container ship / Global	2.229 tonne.km	2,229 km based on weighted average of sea transport to the two export nations (Malaysia: Sihanoukville Autonomous Port to Bangkok Port; Taiwan: Sihanoukville Autonomous Port to Taipei port)

Recyclers

Recycling processing in SMEs within Cambodia is highly manual, reducing the inputs required compared with automated, mechanised systems. However, inputs are still required for plastic washing and cleaning, as well as the heat and electricity required to remelt the plastic and produce plastic pellets. The datasets applied to model the inputs into and emissions from recycling are listed in Table 13. Data collected from Pakistani SME recyclers shows an overall (weighted average) yield from the recycling process of 83% (i.e. the kilogram of plastic waste input yields 0.825 kg of recyclate) [Minimum: 75%; Maximum: 95%][9].

Avoided processes according to system expansion: The plastic recyclate produced is used by manufacturers for the production of various plastic items. As such, the recyclate offsets virgin plastic production that would have been used as an input by these manufacturers. The model for virgin plastic avoided through the recycling of plastic is based on the ecoinvent virgin PET and HDPE datasets (*Polyethylene terephthalate, granulate, amorphous / Global* & *Polyethylene, high density, granulate / Global*). PET and HDPE are used in this offset modelling, as they are the two most recycled polymers in Cambodia and other developing nations within Asia (Aryan et al., 2019; Hashmi et al., 2023; iDE, 2024; Majeed et al., 2018; Seng et al., 2018).

[9] Secondary data suggested a similar, although slightly higher, yield of 89% (i.e. the kilogram of plastic waste input yields 0.889 kg of recyclate) ((Aryan et al., 2019; PLACES, 2023) and ecoinvent-SRI dataset (Plastic granulate, unspecified, recycled, informal sector / India)).

Currently the split of polymers produced by recyclers is unknown and therefore it is assumed that 50% of plastic input is polyethylene, while the remaining 50% is polyethylene terephthalate (PET). This assumption is tested with sensitivity analysis (see Section 4.3).

Almost all plastic recyclate is lower quality than virgin plastic, due to contamination within the recyclate and damages to the polymer chain caused by the initial use phase, exposure to sun, water and chemicals, and/or the heating process employed by recyclers. This lower quality means that the recyclate is utilised for lower value applications (e.g. plastic bricks and furniture instead of food containers, fibres instead of food-grade bottles; irrigation pipes instead of food containers). The one exception is food-grade rPET produced in advanced mechanical recycling plants, which directly replaces virgin PET. For this reason, it is important to account for the lower quality of the recyclate produced, utilising quality ratios.

These quality ratios vary depending on the material processed and type of recycling employed, as summarised in Table 13. The quality of the incoming plastic waste also plays a role, as source separated plastic waste is less likely to have been damaged by environmental factors prior to being received by recyclers (e.g. unlikely to have lay in the sun for months prior to being collected) and the lower incoming contamination levels mean that the recyclate is less likely to contain contaminants. The dirty plastic waste, generally picked from waste stream, utilised by Cambodian recyclers on the other hand is more likely to have residual contamination even after cleaning. It may be noted that the incoming quality of plastic waste also impacts the processing yields, as a higher share of incoming material is lost when the incoming material is highly contaminated. These losses are both from the mass of dirt (organic matter and debris) attached to received plastic and from the disposal of plastic that does not meet specification (e.g. wrong polymer type) or cannot be effectively cleaned.

In this case a quality ratio of 0.76 is utilised for Cambodian SME recycling. When also accounting for yields, this effectively means that for every kilogram of plastic processed by Cambodian recyclers, 0.63 kilograms of virgin plastic are offset. Both the yield and quality ratio utilised are tested with sensitivity analysis (see Section 4.3).

Table 12: Plastic recyclate quality ratios

Recycling method	Quality ratio	Reference
Low-technology mechanical recycling in SMEs	0.76	(Majeed et al., 2018; PLACES, 2023) and Sphera dataset (*Recycling plastic (unspecified), waste management, technology mix, at plant, collection, sorting, transport, washing, granulation, pelletization / Asia*) Consultation with Cambodian SME recyclers also revealed that recyclate is commonly used for lower-grade applications (e.g. plastic bricks)
Higher-technology mechanical recycling – LDPE film	0.75	(European Commission, 2018)
Higher-technology mechanical recycling – Non-film	0.9	
Closed-loop PET recycling	1	

Table 13: Inventory inputs into waste transportation to recyclers within Cambodia [per kilogram plastic waste processed]

Inputs: Materials & fuels	ecoinvent dataset used / Geography	Value	Reference
Water	Tap water / Cambodia (*adapted from Indian dataset*)	1.676 kg	(Aryan et al., 2019; Hashmi et al., 2023; Majeed et al., 2018) and ecoinvent-SRI dataset (*Plastic granulate, unspecified, recycled, informal sector / India*)
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state / Global	2.000E-2 kg[10]	(Aryan et al., 2019; Majeed et al., 2018)

[10] Secondary data value of 1.082E-2 kg (Aryan et al., 2019) and ecoinvent-SRI dataset (*Plastic granulate, unspecified, recycled, informal sector / India*). Only one primary data point.

Sodium chloride	Sodium chloride, powder/ Global	7.760E-2 kg	ecoinvent-SRI dataset (*Plastic granulate, unspecified, recycled, informal sector / India*)
Formic acid	Formic acid / Global	7.534E-5 kg	ecoinvent-SRI dataset (*Plastic granulate, unspecified, recycled, informal sector / India*)
Potassium aluminium sulphate	Chemical, inorganic / Global	1.000E-2 kg	Data collected from 12 Cambodia SME recyclers
Infrastructure	Waste preparation facility, construction / Global	1.78E-9 units	ecoinvent dataset (*Waste preparation facility / Global*)[11]
Inputs: Electricity & heat	**ecoinvent dataset used / Geography**	**Value**	**Reference**
Electricity	Electricity, low voltage / Cambodia	0.394 kWh[12]	Data collected from 12 Cambodia SME recyclers
LPG	Heat, central or small-scale, natural gas, heat production, LPG, at boiler fan burner non-modulating <100kW / Cambodia (*adapted from Global natural gas dataset)*	0.343 MJ	(Aryan et al., 2019; Hashmi et al., 2023; Majeed et al., 2018) and ecoinvent-SRI dataset (*Plastic granulate, unspecified, recycled, informal sector / India*)
Diesel	Diesel, burned in building machine / Global	0.045 MJ	(Aryan et al., 2019; Hashmi et al., 2023; Majeed et al., 2018) and ecoinvent-SRI dataset (*Plastic granulate, unspecified, recycled, informal sector / India*)
Emissions to air	**ecoinvent dataset used / Geography**	**Value**	**Reference**
Ethyle-benzene	Benzene, ethyl-	1.154E-09	ecoinvent-SRI dataset (*Plastic granulate, unspecified, recycled, informal sector / India*)
Carbon disulfide	Carbon disulfide	4.490E-10	
Dichloromethane	Methane, dichloro-, HCC-30	1.299E-09	
Toluene	Toluene	1.658E-09	
Large particulates	Particulates, > 10 um	2.763E-05	
Medium particulates	Particulates, > 2.5 um, and < 10um	8.069E-07	
Emissions to water	**ecoinvent dataset used / Geography**	**Value**	**Reference**
BOD	BOD5 (Biological Oxygen Demand) / Cambodia	8.398E-05	ecoinvent-SRI dataset (*Plastic granulate, unspecified, recycled, informal sector / India*)
Chloride	Chloride	4.791E-05	
COD	COD (Chemical Oxygen Demand) / Cambodia	3.174E-04	
DOC	DOC, Dissolved Organic Carbon	1.058E-04	
Nitrogen	Nitrogen, atmospheric	5.500E-05	
Oils	Oils, biogenic	1.993E-05	
Phosphorous	Phosphorus / Cambodia	2.847E-06	
Sodium	Sodium (I)	3.198E-05	
Solids	Suspended solids, unspecified	3.687E-04	
TOC	TOC, Total Organic Carbon	1.058E-04	
Outputs: Waste treatment	**ecoinvent dataset used / Geography**	**Value**	**Reference**
Waste to landfill	Municipal solid waste, treatment of municipal solid waste, unsanitary landfill, very wet infiltration class (1000mm) / Global	0.160 kg	Data collected from 12 Cambodia SME recyclers – Split between disposal types based on national waste management data (Table 2)

[11] Likely an overestimate of infrastructure, including machinery, as based on high technology waste processing in Europe.
[12] Secondary data value of 0.181 kWh (Aryan et al., 2019; Hashmi et al., 2023; Majeed et al., 2018) and ecoinvent-SRI dataset (*Plastic granulate, unspecified, recycled, informal sector / India*). Primary data range: 0.035 – 0.476 kWh/kg input plastic.

Waste to incineration	Municipal solid waste, treatment of municipal solid waste, municipal incineration / Global	0.015 kg	
Wastewater	Wastewater, average / Cambodia (*adapted from Global dataset*)	1.676 L	Water balance

3.1.8 Higher technology open-loop recycling

Although not commonly occurring in Cambodia, and especially not amongst SME recyclers within Cambodia, it is possible for mechanical recycling to utilise more automated, technologically advanced systems for the mechanical recycling process. These systems may include automated sorting systems; automated washing systems; and high technology melting and pelletisation systems. Although these systems require more capital outlay, they typically result in higher quality recyclate, as the plastic waste is more thoroughly sorted and cleaned than possible within manual systems. Furthermore, the melting and pelletisation systems are carefully monitored to ensure the polymer is not over-heated and therefore damaged by the remelting process. However, the systems still produce recyclate of lower quality than virgin plastic (i.e. open-loop recycling).

As no primary data is available on this form of mechanical recycling from Cambodian recyclers, the current mechanical recycling datasets in ecoinvent (*Polyethylene terephthalate, granulate, amorphous, recycled / Global* & *Polyethylene, high density, granulate, recycled / Global*) were adapted to the Cambodia geographical context. These datasets model relatively high technology mechanical recycling, as occurring in Europe and other developed nations. The geographical adaptations involved changing relevant inputs from nature (water and cooling water), inputs (electricity) and waste treatment (municipal solid waste and wastewater treatment) to the Cambodian-linked dataset (e.g. *Water / Global* to *Water / Cambodia*).

It is assumed the upstream collection, junkshop and transportation systems are the same for SME recycling and high technology recycling.

Avoided processes according to system expansion: As with the Cambodian SME recycling, the plastic recyclate produced would be utilised by manufacturers for the production of various plastic items. As such, the recyclate offsets virgin plastic production that would have been used as an input by these manufacturers. This virgin plastic offset is modelled based on the ecoinvent virgin PET and HDPE datasets (*Polyethylene terephthalate, granulate, amorphous / Global* & *Polyethylene, high density, granulate / Global*).

As with SMA recycling, it is assumed that 50% of input is polyethylene, while the remaining 50% is polyethylene terephthalate (PET). This assumption is tested with sensitivity analysis (see Section 4.3).

The produced recyclate has a quality ratio of 0.9 (CFF default - Table 13), with a yield of 80% for PET and 94% for HDPE. Therefore, when accounting for yields, this effectively means that for every kilogram of plastic processed, 0.36 kilograms of virgin PET and 0.42 kilograms of virgin HDPE are offset. The quality ratio utilised is tested with sensitivity analysis (see Section 4.3).

Export market recyclers

It is assumed that all plastic waste exported from Cambodia, to markets such as Malaysia and Taiwan, is processed by larger, higher technology recyclers. For this reason, recycling in the export markets is also based on the current mechanical recycling datasets in ecoinvent (*Polyethylene terephthalate, granulate, amorphous, recycled / Global* & *Polyethylene, high density, granulate, recycled / Global*), adapted to the relevant geographical contexts. This adaptation assumes that 73% and 27% of plastic waste is processed in Malaysia and Taiwan respectively (ITC, 2025). Avoided virgin plastic production is also accounted for based on the ecoinvent virgin PET and HDPE datasets (*Polyethylene terephthalate, granulate, amorphous / Global* & *Polyethylene, high density, granulate / Global*), assuming a 50%:50% split between PET and HDPE and a quality ratio of 0.9 (CFF default - Table 13).

3.1.9 Closed-loop PET recycling

Closed-loop PET recycling is a form a mechanical recycling that utilises advanced processes to recycle PET bottles into bottle-grade rPET (i.e. food-grade to food-grade recycling). These systems utilise advanced automated sorting and washing systems to pre-process the incoming PET bottles, as the rPET recyclate needs to be nearly completely contamination free (i.e. cannot be contaminated by debris, organics or other polymers, such as PVC). The remelting systems also contain advanced processing systems, such as vacuum extraction, to remove contamination and chemicals from the remelted polymer prior to pelletisation. These systems therefore produced recyclate of equivalent grade to virgin PET (i.e. closed-loop recycling).

As no primary data is available on this form of mechanical recycling from Cambodian recyclers, the current rPET recycling dataset in ecoinvent (*Polyethylene terephthalate, granulate, bottle grade, recycled / Global*) was adapted to the Cambodian geographical context. The geographical adaptations involved changing relevant inputs from nature (water and cooling water), inputs (electricity) and waste treatment (municipal solid waste and wastewater treatment) to the Cambodian-linked dataset (e.g. *Water / Global* to *Water / Cambodia*).

It is assumed the upstream collection, junkshop and transportation systems are the same for SME recycling and closed-loop recycling.

Avoided processes according to system expansion: The rPET produced would be utilised by manufacturers for the production of various plastic items, including food-grade bottles. As such, the recyclate offsets virgin PET production that would have been used as an input by these manufacturers. This virgin plastic offset is modelled based on the ecoinvent virgin PET bottle-grade dataset (*Polyethylene terephthalate, granulate, bottle grade / Global*).

As with higher technology open-loop recycling, it is assumed that 50% of the plastic waste input is polyethylene, terephthalate (PET). This assumption is tested with sensitivity analysis (see Section 4.3). The polyethylene plastic waste input still undergoes higher technology open-loop recycling (i.e. its processing and output is unchanged from high technology open-loop recycling).

The produced PET has a quality ratio of 1, as it is equivalent to virgin PET, (CFF default - Table 13) with a yield of 82%. Therefore, when accounting for yields, this effectively means that for every kilogram of plastic processed, 0.42 kilograms of virgin bottle-grade PET and 0.42 kilograms of virgin HDPE (recycled via higher technology open-loop recycling) are offset.

3.2 Impact assessment

The purpose of impact assessment is to group and aggregate the LCI data according to their contribution to predefined environmental impact categories. The selection of environmental impact categories is governed by the need to be comprehensive, in that they should cover all relevant environmental issues related to the product system. Several different life cycle impact assessment (LCIA) methods have been developed by research groups around the world. The definition of impact categories varies from one method to the next, but environmental LCIA methods generally cover the following broad areas of concern:

- **Damage to human health**, which occurs through a variety of effects, including the release of substances toxic to humans, substances that destroy the ozone layer, substances that cause respiratory illnesses and that cause global climate change;

- **Damage to ecosystems**, which occurs through a variety of effects including the release of substances toxic to ecosystems, the release of acidifying substances and excessive macronutrients, as well as ecosystem impacts arising from water deprivation and land transformation/occupation; and
- **Resource depletion**, representing the concern around availability of non-renewable resources for future generations, and the use of renewable resources beyond their carrying capacity.

The IMPACT World+ impact assessment method, developed by the International Reference Centre for Life Cycle Assessment and Sustainable Transition (CIRAIG) and the Technical University of Denmark (DTU), is applied in this study. IMPACT World+ is the result of an update of three existing, well recognised LCA methods, namely: IMPACT 2002+, EDIP and LUCAS.

IMPACT World+ is chosen for application in this study as it is a global methodology, unlike region-specific methods such as the Environmental Footprint (EF) method[13], which still provides region-specific characterisation factors (i.e. results are regionalised to the study location). The method calculates impacts at both the midpoint and damage (effect or endpoint) level, allowing for the estimation of potential damages to key areas of protection (AoP). Together this provides a holistic understanding of life cycle environmental impacts, allowing for determination of specific environmental impacts of interest (e.g**. climate change impact; water scarcity**), while also assessing the overall impact of all environmental impact categories on human health, ecosystem quality, and resource & ecosystem services.

The 25 impact categories that currently constitute the IMPACT World+ impact assessment method are summarised in Table 14. As can be seen from the table, 19 of these impact categories are reported at the midpoint level, while six of the impact categories are only reported at the damage level, to allow the quantification of AoP impacts. These impact categories and the linkages between midpoints and AoPs are summarised in Figure 3.

Currently, **the human health and ecosystem quality AoPs**[14] are quantified from 22 of the impact categories, while the resource & ecosystem services AoP is not quantified. As such, for resource & ecosystem services, the **fossil and nuclear energy use** midpoint impact is utilised to represent non-renewable resource depletion.

For human health and ecosystem quality AoPs, impacts are also presented based on the IMPACT World+ deterministic weightings. Although any weighting scheme is not wholly science based and inherently involves value judgements, reflecting the cultural, political and other values and preferences of those assigning the weights, weighting is beneficial as it allows for direct comparison, and even aggregation, of the AoPs impacts.

Impact assessment is carried out in SimaPro 9. The implementation of the EF impact assessment method in SimaPro is based on the IMPACT World+ 2.1 release (November 2024).

[13] EF was developed by the European Commission and is therefore European-focused.

[14] It may be noted that ecosystem quality impacts include the microplastic characterization factors developed as part of MariLCA. The inclusion of plastic impact categories is an important step towards more holistic quantification of plastic impacts in LCA, and a further reason why the IMPACT World+ method is deemed best for this study. The impact assessment method is based on the quantities of microplastics released into the environment. Microplastic quantities include both primary microplastics (i.e. microplastics released directly into the environment from microplastic-containing products, tyre abrasion, textile washing etc.) and secondary microplastics (i.e. microplastics released from the fragmentation of macroplastics in the environment). Current plastic footprint methodologies allow for the estimation of primary microplastic quantities using default values, loss rates and release rates for tyres and textiles; however, secondary microplastic quantities cannot yet be estimated due to a lack of data. As secondary microplastics are the only significant source of microplastics within the systems considered, within this study microplastic quantities and the associated impacts are not quantified.

Table 14: Description of impact categories included in the IMPACT World+ impact assessment method[15]

Environmental impact category	Impact category indicator and units	Areas of Protection (AoP) impacted
Climate change, short-term	Radiative forcing as Global Warming Potential (GWP 100-year) in kg CO_2 equivalents	Human health Ecosystem quality
Climate change, long-term	Long-term cumulative temperature changes as Global Temperature Potential (GTP 100-year) in kg CO_2 equivalents	Human health Ecosystem quality
Fossil and nuclear energy use	Fossil energy use (abiotic fossil fuel resource depletion) in MJ deprived	
Mineral resources use	Mineral resource use (abiotic mineral resource depletion) in kg deprived	
Photochemical ozone formation	Photochemical ozone creation potential (POCP) in kg non-methane volatile organic compound (NMVOC) equivalents	Human health
Ozone layer depletion	Ozone depletion potential (ODP) in kg CFC-11 equivalents	Human health
Freshwater ecotoxicity	Ecosystem toxicity potential in Comparative Toxic Unit for ecosystems (CTUe)	Ecosystem quality
Human toxicity cancer	Estimated increase in morbidity in the human population per unit mass of chemical emitted in Comparative Toxicity Unit for humans (CTUh)	Human health
Human toxicity non-cancer	Estimated increase in morbidity in the human population per unit mass of chemical emitted in Comparative Toxicity Unit for humans (CTUh)	Human health
Freshwater acidification	Change in freshwater pH (freshwater acidification) in kg SO_2 equivalents	Ecosystem quality
Terrestrial acidification	Change in terrestrial pH (terrestrial acidification) in kg SO_2 equivalents	Ecosystem quality
Freshwater eutrophication	Increase in nutrients (phosphorous) in freshwater end compartment in kg PO_4 equivalents (phosphorous considered the limiting factor in freshwater bodies)	Ecosystem quality
Marine eutrophication	Increase in nutrients (nitrogen) in coastal marine end compartment in kg N equivalents (nitrogen considered the limiting factor in marine bodies)	Ecosystem quality
Particulate matter formation	Estimated increased in human health impacts from particulates in kg of particles of less than 2.5 microns (PM2.5) emitted	Human health
Ionizing radiation	Ionising radiation potential in Bq C-14 equivalents	Human health Ecosystem quality
Land transformation, biodiversity	Biodiversity impacts from land transformation in square meters per year (m^2.year) of arable land	Ecosystem quality
Land occupation, biodiversity	Biodiversity impacts from land use in square meters per year (m^2.year) of arable land	Ecosystem quality
Water scarcity	Deprivation-weighted water consumption in global m^3 equivalents	*See water availability impact category*
Plastic physical effects on biota	Physical impacts of microplastics on biota in Comparative Toxic Unit for ecosystems (CTUe)	Ecosystem quality
Fisheries impact	Only as endpoint impacts	Ecosystem quality
Marine acidification	Only as endpoint impacts	Ecosystem quality
Marine ecotoxicity	Only as endpoint impacts	Ecosystem quality
Terrestrial ecotoxicity	Only as endpoint impacts	Ecosystem quality
Thermally polluted water	Only as endpoint impacts	Ecosystem quality
Water availability	Only as endpoint impacts	Human health Ecosystem quality

[15] Further details on the IMPACT World+ are available from the project website (https://www.impactworldplus.org/) and the associated publication (https://link.springer.com/article/10.1007/s11367-019-01583-0).

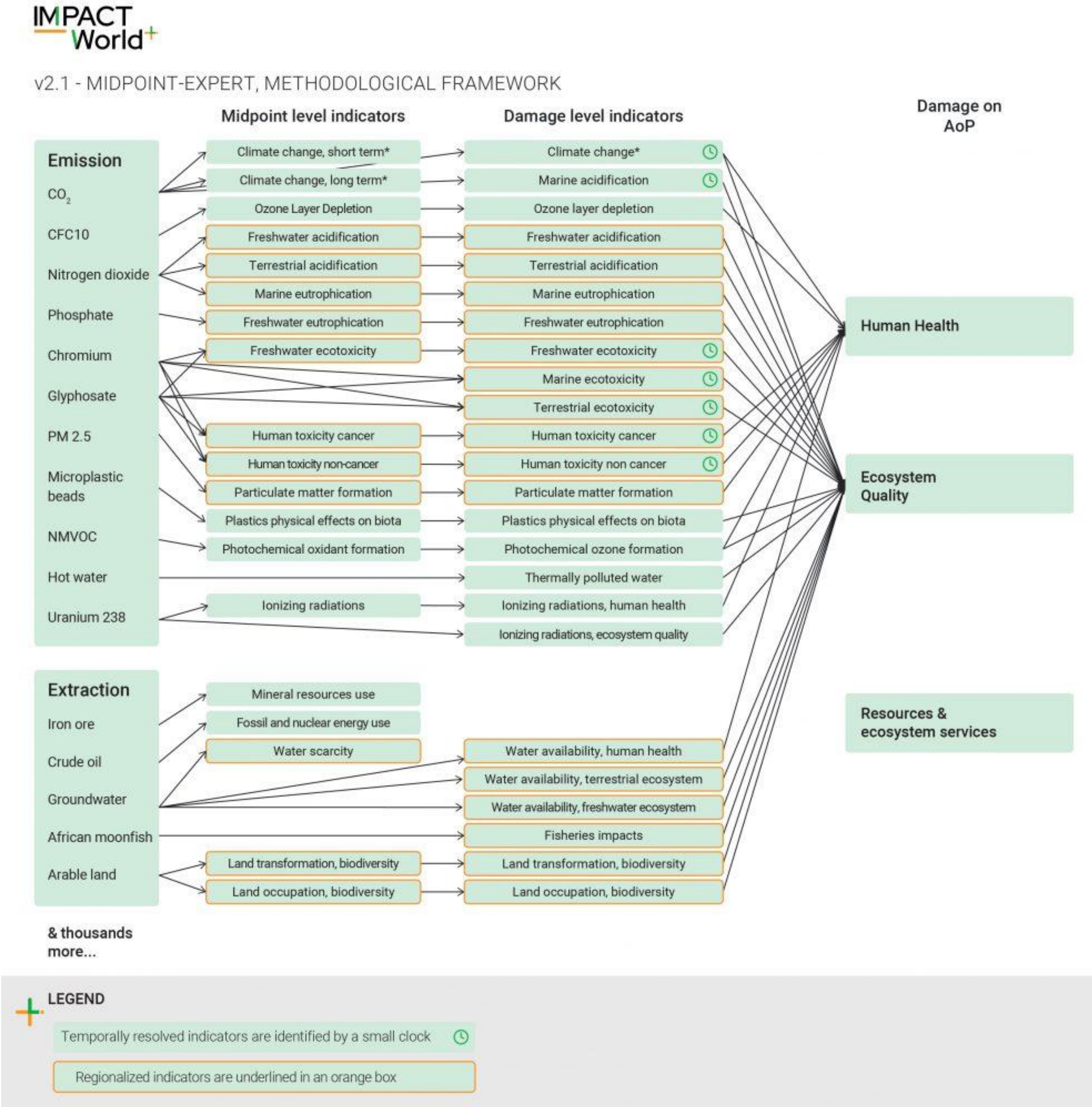

Figure 3: IMPACT World+ impact assessment methodology impact categories and framework (CIRAIG and DTU, 2025)

3.2.1 Plastic and circularity impacts

Current LCIA methods, including the IMPACT World+ method, do not fully quantify the impacts of plastics. Whilst LCA results reflect the environmental impacts of producing and disposing of plastics, only recently, with the development of the MariLCA *Physical impacts of microplastics on biota* characterization factors (September 2023), have any human health or ecosystem quality impacts from mismanaged plastics degrading in soils, waterways and oceans been included in selected LCIA methods[16]. These characterization factors are also limited, as they only consider impacts from microplastics within water, and therefore ignore impacts from macroplastics or any plastics

[16]Currently only the IMPACT World+ and GLAM methodologies.

within the terrestrial environment. As mentioned above, secondary microplastics (i.e. microplastics resulting from macroplastic releases and subsequent breakdown) are the only significant source of microplastics within the systems considered; however, these quantities cannot yet be estimated due to a lack of data. Within this study microplastic quantities and the associated impacts can therefore not be quantified.

To fill this gap and provide a more holistic understanding of the plastic waste management options, the following factors are also investigated and reported alongside the life cycle environmental impacts:

- **Plastic footprint**: Quantity of macroplastics released into the natural environment from mismanaged plastic waste according to the Plastic Footprint Network (Plastic Footprint Network, 2024) and Plastic Leak Project (Plastic Leak Project, 2020) methodologies[17], which also align with UNEP's *National Guidance for Plastic Pollution Hotspotting and Shaping Action*
- **Material Circularity Indicator (MCI)**: Representation of the circularity of the plastic system, including plastic waste management, according to the MCI methodology (Ellen MacArthur Foundation and ANSYS Granta, 2019)[18]

Neither of these factors reflect the potential impacts of plastic in the natural environment. However, plastic releases into the environment are seen as the first step to understanding overall plastic impacts, even if the impacts of these releases cannot yet be quantified in terms of human health, ecosystem quality and non-renewable resource impacts (i.e. it is a proxy for the inherent risk for plastics to end up in the environment, where they can cause environmental impacts). The MCI meanwhile provides a quantitative value for the circulatory a system, thus providing information on how decoupled a system is from linear ("take-make-waste") economy and how much value is extracted by the waste management option.

4 Interpretation

This section provides the life cycle results. It starts with a presentation of the impacts of current plastic waste management practices in Cambodia (i.e. split between plastic landfilled, dumped, recycled etc.). Following this, the results for the six waste management options (landfill, incineration with energy recovery, RDF production and three-levels of mechanical recycling) are analysed according to how they compare with Cambodia baseline scenario and with each other. Discussions are also provided on what is making up the environmental impacts of the waste management systems and how these could be mitigated.

4.1 Baseline scenario

The aggregated life cycle human health and ecosystem quality impacts of current plastic waste management within Cambodia is presented in Figure 4. These results show that close to two-thirds (63%) of these impacts are cause by short- and long-term climate change impacts, while other human toxicity (cancer and non-cancer) and freshwater ecotoxicity (a component of other ecosystem quality) are the second and third largest source of impacts respectively. Human toxicity and freshwater ecotoxicity impacts are both linked to heavy metals released to air and soil during burning of plastic.

The results also reveal that the bulk of impacts (89%) occur from the open burning of plastic waste, even though open burning only accounts for 23% of plastic waste management in Cambodia (Table 2). This phenomenon is linked to plastic being relatively inert within landfill and dump sites, meaning that few emissions occur from plastic that is ether landfilled or openly dumped. As such, although 64% of plastic waste is either landfilled or openly

[17] Based on current data, the default is that 10% of mismanaged waste is leaked to the marine environment.
[18] The MCI method complies with the new ISO 59020:2024 *Circular economy – Measuring and assessing circularity performance* Standard.

dumped, this plastic only accounts for 4% of human health and ecosystem quality impacts. The burning of plastic, especially in an uncontrolled and inefficient manner, on the other hand results in the release of large quantities of emissions to air and soil. These emissions include greenhouse gas emissions (carbon dioxide and methane principally) from the combustion of a carbon-rich material, volatile organic compounds, particulates, and heavy metals that are contained with plastics. Together these emissions pose significant human health and ecosystem quality impacts.

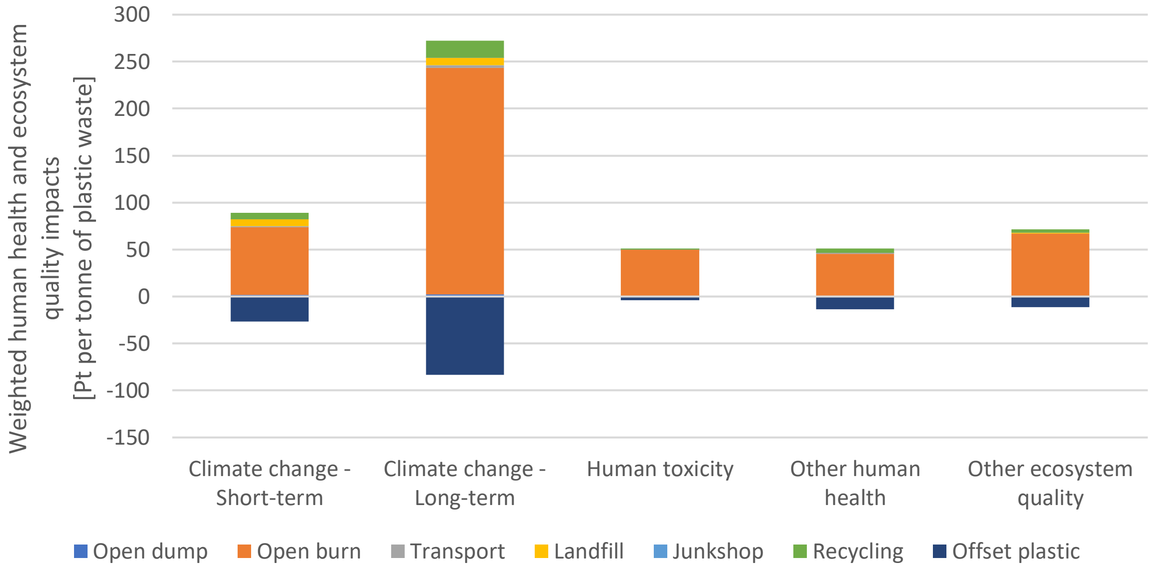

Figure 4: Aggregated life cycle human health and ecosystem quality impacts of current Cambodian plastic waste management, broken down by life cycle stage, disposal type and damage category[19]

These results also show that the transportation of plastic waste to landfill and recyclers (including recyclers in other countries) does not significantly contribute (1%) to impacts. However, plastic recycling, which currently only accounts for 9% of plastic waste generated in Cambodia, results in impact reductions of around 20%. The recycling process itself results in life cycle environmental impacts, primarily due to the use electricity and fuels in the processing stage. These impacts are more than offset by avoided virgin plastic production, which is equivalent to 26% of total plastic waste management impacts. As such, even in this baseline scenario, the impact of plastic recycling can already be seen, both by avoiding plastic waste being burnt or otherwise disposed of, and through the production of recyclate that offsets virgin plastic production.

When considering non-renewable resource depletion (Table 15), through the *fossil and nuclear energy use* impact category[20], these impacts occur in stages where fossil energy is utilised, with no impacts directly from any disposal route (i.e. no impacts from emission releases to air, soil and water). As such, in the baseline scenario almost four-fifths (79%) of impacts arise from energy consumption within the recycling process, while energy consumption in transportation (15%) and landfilling (5%) account for remaining impacts. Virgin plastic production is a fossil fuel intensive process, as it utilises fossil fuel derived materials (ethylene etc.) as feedstocks and requires large energy inputs. The amount of fossil energy saved through offsetting virgin plastic production, even in the baseline scenario

[19] Unit of Points. The IMPACT World+ methodology includes weighting and normalization for human health and ecosystem impacts, which take these impacts down to a single, common unit (points) and allow for summation of impacts into a "single-score". This single score represents all human health and ecosystem quality impacts, including climate change, water scarcity, eutrophication, acidification etc. As discussed in Section 3.2, this does not include non-renewable resource depletion impacts.
[20] Similar trends are also seen in the other non-renewable resource depletion midpoint impact category, *mineral resources use*.

where recycling rates are low (9%), means that the net fossil energy use impact of plastic waste management in Cambodia is negative.

Table 15: Summary of life cycle environmental impacts of current Cambodian plastic waste management, broken down by life cycle stage, disposal type and damage category

Environmental impact category	Units	Open dump	Open burn	Transport	Landfill	Junkshop	Recycling	Offset plastic	Total
Climate change	kg CO_2e	19	558	7	72	0	54	-206	**503**
Long-term climate change	kg CO_2e	6	528	6	23	0	40	-181	**424**
Water scarcity	m^3e	0	0	0	0	0	5	-42	**-36**
Human health	DALY	5.0E-05	5.0E-03	5.5E-05	1.8E-04	1.8E-06	3.6E-04	-1.5E-03	**4.1E-03**
Ecosystem quality	PDF.m^2.year	8	748	6	20	1	43	-176	**651**
Fossil and nuclear energy use	MJ deprived	0	0	88	30	2	446	-4,670	**-4,104**

The baseline scenario has a plastic footprint of 6.4% of plastic leaked to the marine environment, based on the fact that 64% of plastic waste is currently mismanaged or poorly managed[21]. Due to the low recycling rate, the MCI is also near linear at 3%.

4.2 Waste management options

The aggregated life cycle human health and ecosystem quality impacts of the six plastic waste management options are presented in Figure 5. As discussed in Section 2.2.3, these results are presented with system expansion applied, meaning that allocation is avoided by expanding the system boundary to include the primary materials displaced when secondary materials are produced. The producing system is credited with avoiding the production of primary materials (i.e. the burdens associated with producing the avoided materials are subtracted from the burdens arising in the system producing the secondary materials). This accounts for the net human health and ecosystem quality impacts being negative for the three recycling options (i.e. recycling results in overall positive human health and ecosystem impacts), where the burdens associated with producing the virgin plastics are higher than the burdens associated with producing recyclate. Similarly, the net human health and ecosystem quality impacts are negative for RDF production, as the burdens associated with producing and combusting fossil fuels are higher than the burdens associated with producing and combusting the RDF.

Figure 5 shows that for the recycling options, the impacts are dominated by the avoided virgin plastic. The burdens associated with producing the avoided virgin plastic are the reason that all three recycling options show substantially lower life cycle impacts than baseline plastic waste management scenario. In the case of incineration with energy recovery, the impacts are dominated by impacts from the incineration process, which are not offset by the avoided grid electricity generation. The burdens associated with incineration are chiefly from direct emissions to air, including greenhouse gases, nitrogen-based gases, sulphur-based gases and heavy metals, resulting from combustion of plastic. RDF production and use impacts are dominated by the impacts from RDF (plastic) combustion, which as with incineration are chiefly from direct emissions to air, with electricity consumption in process accounting for the bulk of remaining impacts. However, these impacts are offset by avoided fossil fuel production (13%) and combustion (85%). Combustion emissions are primarily from direct environmental emissions, especially greenhouse gas, particulate and sulphur-based gases to air.

[21] This includes waste send to landfill, as current landfills are poorly managed (unsanitary landfills).

The three recycling options all show low human health and ecosystem quality impacts, with the closed-loop mechanical recycling option (closed-loop PET recycling combined with high technology HDPE recycling) showing the lowest overall impacts. This option has similar burdens associated with it when compared with the high technology mechanical recycling option but has the highest avoided burdens from the virgin plastic displaced by recyclate.

Greater detail on the impacts per midpoint category and AoP are provided in the sections below.

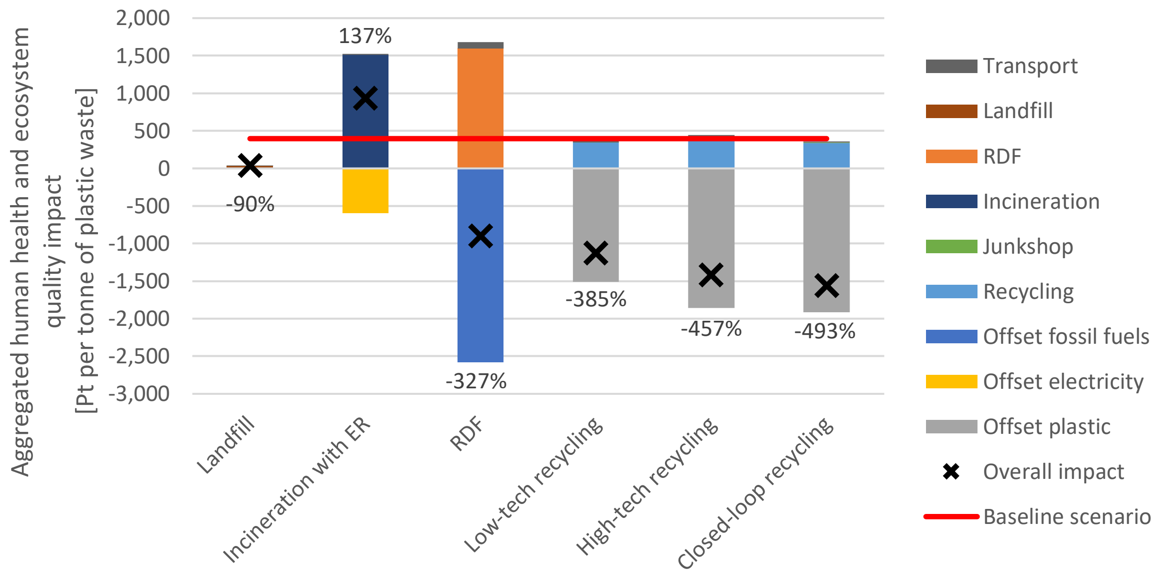

Figure 5: Aggregated life cycle human health and ecosystem quality impacts, broken down by life cycle stage, for plastic waste management options in Cambodia. Crosses represent the net aggregated result of each option, with percentages reflecting the difference in impact relative to the Cambodia baseline scenario for each option.

4.2.1 Climate change

Short-term and long-term climate change impacts for the six waste management options are shown in Figure 6 and Figure 7 respectively, which show that RDF production and the three recycling options have negative net climate change impacts. Short-term climate impacts are based on global warming potentials (100-year GWPs), as used in typical carbon accounting and greenhouse gas inventories, and is a measure of additional heat absorbed by the Earth's atmosphere over time. Long-term climate change impacts are based on global temperature potentials (100-year GTPs)[22] and is therefore a measure of the long-term temperature change associated with the additional greenhouse gases in the atmosphere. As these two impact categories follow the same trends, discussion focuses on the short-term climate change impacts below (i.e. percentages are based on short-term climate change impacts).

In the baseline scenario, the majority of climate change impacts (79% for short-term and 87% for long-term) result from open burning (combustion) of plastic waste. Incineration with energy recover is the only option investigated that increases the climate change impacts of plastic waste management, linked to the greenhouse gases emitted

[22] GTP accounts for how long greenhouse gases remain in the atmosphere. It also requires modelling of how the climate system responds to increase greenhouse gas concentrations (i.e. climate sensitivity), as well as how quickly the Earth's systems respond, including how the ocean absorbs the increased heat within the Earth's systems.

during the combustion of carbon-rich plastic. These emissions are not offset by the grid electricity[23] avoided, with avoided emissions equivalent to only a third (32%) of the climate change impacts of incineration.

The landfilling, RDF production and three recycling options result in lower climate change impacts than baseline plastic waste management. Impacts associated with landfilling are lower due to the inert nature of plastic, meaning that there is minimal degradation of plastic within landfill and consequently low levels of greenhouse gas emissions to air. These direct emissions still account for the bulk of climate change impacts from landfilling, with direct fuel use in landfilling equipment the second largest source of impacts.

RDF production and combustion has higher impacts than the baseline scenario, which primarily result from the combustion of the plastic RDF material (87%) and electricity consumption during the production phase (9%). As with incineration, the combustion emissions are due to the greenhouse gases emitted during the combustion of carbon-rich plastic. These impacts are however more than offset by avoided fossil fuel production and combustion (coal: 36%; fuel oil: 64%), resulting in net negative climate change impacts from RDF. Avoided fossil fuel production accounts for only 16% of these offset impacts, linked to direct emissions from (e.g. coal methane, flaring) and energy use for extraction. Avoided direct emissions from combustion account for the bulk (83%) of offset impacts, linked to the greenhouse gas emissions emitted from the combustion of carbon-rich fossil fuels. As such, **in cases where plastics are not recyclable with current technologies (e.g. multi-layer plastics), RDF production is the best option in terms of climate change impact**.

The recycling options have impacts equivalent to (closed-loop recycling) or higher than (low-technology and high technology recycling) the baseline scenario; however, their net climate change impacts are dominated by the climate change impacts avoided through virgin plastic offsetting. These avoided emissions are between four and six times higher than impacts associated with transportation, sorting and recycling, resulting in a net positive effect on climate change for all three recycling options. **The closed-loop recycling option results in the highest climate change benefit**.

[23] Cambodia grid emission factor: 0.70 kg CO_2e/kWh. Currently around a half of electricity is generated from coal, while a further 7% is from oil- and gas-based generation.

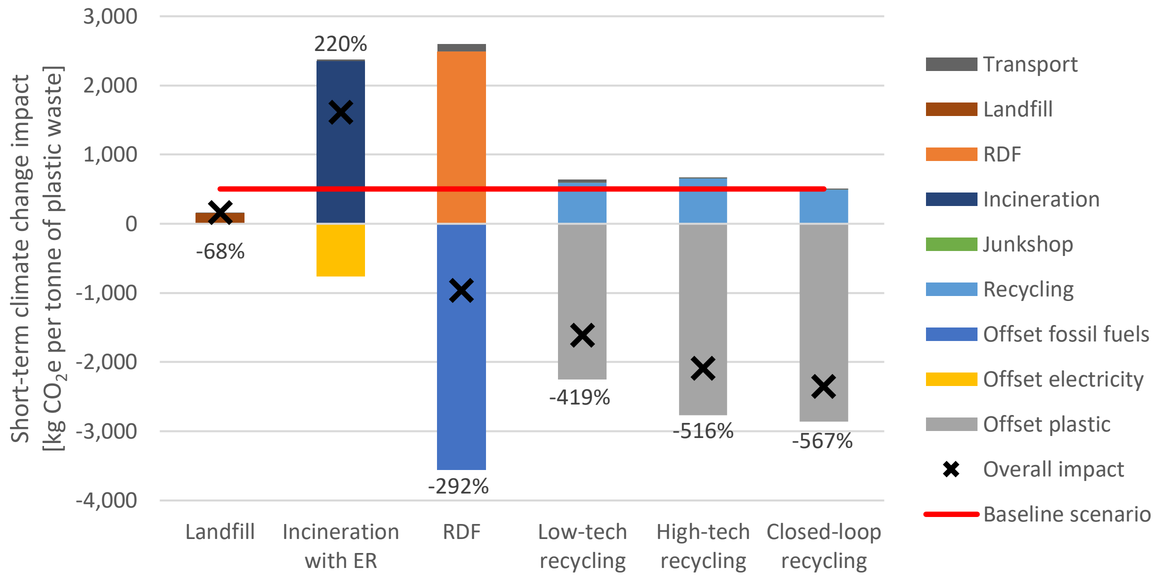

Figure 6: Short-term climate change impacts, broken down by life cycle stage, for plastic waste management options in Cambodia. Crosses represent the net impacts each option, with percentages reflecting the difference in impact relative to the Cambodia baseline scenario for each option.

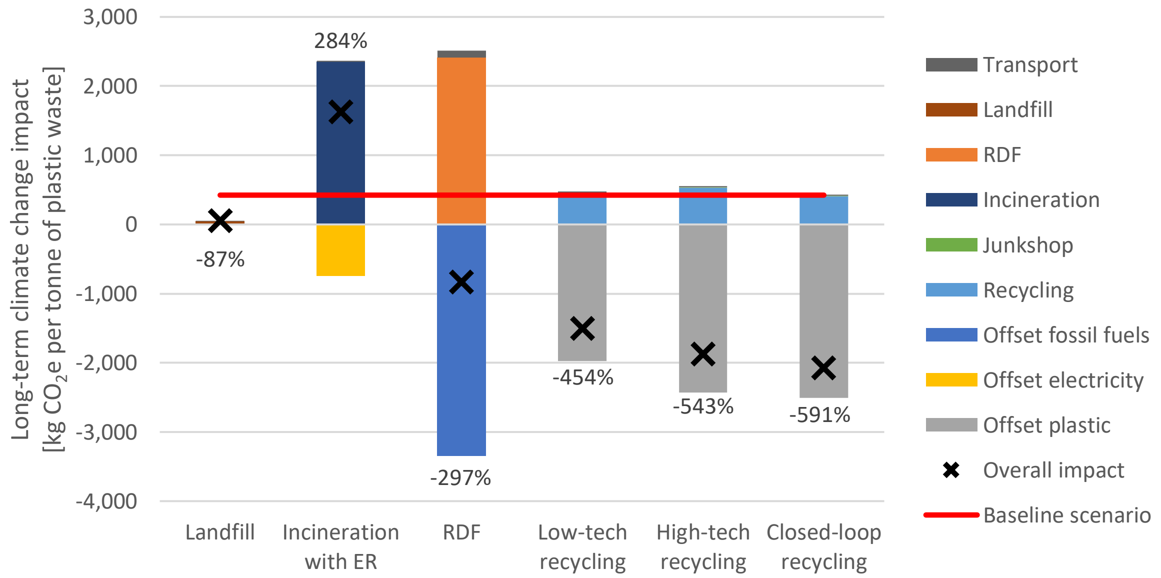

Figure 7: Long-term climate change impacts, broken down by life cycle stage, for plastic waste management options in Cambodia. Crosses represent the net impacts each option, with percentages reflecting the difference in impact relative to the Cambodia baseline scenario for each option.

The impacts associated with the recycling value chain arise primarily from the recycling phase, with impacts from junkshop operations (electricity consumption) and transportation of the material from junkshops to recyclers (diesel consumption in vehicles) accounting for less than 8% of impacts across all three options. Recycling phase impacts principally arise electricity consumption, heat generation and solid waste disposal (Table 16).

For low-technology recycling, as practiced by SMEs in Cambodia, half (55%) of climate impacts result from the use of electricity and fuels, while a third of impacts are from the disposal of waste generated in the process. Energy consumption should therefore be targeted to mitigate climate change impacts from SME recycling, as any improvements in energy efficiency will reduce the associated climate change impacts. Waste disposal impacts arise from the relatively large volume of waste disposed of (0.17 kg/kg plastic waste) and the fact this waste is a mixture of materials, likely with a large organic component[24]. This is linked to the "dirty" nature of incoming plastic waste, which is largely collected from the general waste stream and therefore is contaminated with organic waste and other materials (other polymers, foils etc.). The amount of waste produced, along with associated impacts, can be mitigated by obtaining cleaner plastic items, either through source separated collection or increased upstream pre-processing. Cleaner incoming plastic waste also has the added benefit of improving the quality of output recyclate.

For high technology and closed-loop recycling, around three-quarters of climate impacts are from the use of electricity and fuels, especially electricity from the increased level of mechanisation. As with the low-technology recycling, the primary mitigation route would be targeting energy efficiency to reduce consumption and the associated impacts. It is also possible that larger, mechanised plants could switch to renewable electricity sources, such as solar PV, which would effectively eliminate impacts from electricity consumption.

Table 16: Share of recycling climate change impacts from electricity, heat generation and solid waste disposal

	Low-technology recycling	High technology recycling	Closed-loop recycling
Electricity	48%	67%	55%
Heat	6%	8%	22%
Solid waste	32%	20%	17%
Remaining inputs and outputs	*13%*	*5%*	*6%*

Avoided greenhouse gas emissions are split almost 50%:50% between PET and HDPE across all three recycling scenarios. Avoided PET has high impacts associated with input raw materials (terephthalic acid: 57%; ethylene glycol: 25%), as well as the heat (11%) and electricity (4%) inputs required for processing. Likewise, the avoided HDPE has high associated climate change impacts linked to the ethylene feedstock (77%) and electricity (11%) and steam (5%) inputs required for processing. Due to this, the avoided impacts are significantly higher (350% for low-technology recycling to 560% for closed-loop recycling), than the impacts associated with the recycling value chain (collection, pre-processing and recycling). This results in the net negative climate change impacts for the recycling options.

4.2.2 Water scarcity

Figure 8 shows that water scarcity impacts are higher for landfilling, incineration with energy recovery and RDF production than the baseline scenario, while the three recycling options have net negative water scarcity impacts significantly lower than the baseline scenario.

In the baseline scenario, water scarcity impacts are primarily from recycling processing (92%), even with the small fraction of plastic waste sent for recycling. This impact results from water consumption directly in the processing step (i.e. water use for cleaning and processing, along with the associated wastewater treatment of the contaminated water). These impacts are more than offset by avoided virgin plastic production, resulting in the baseline scenario having a net negative water impact.

Landfilling on the other hand has water scarcity impacts, even if close to negligible. Close to three-quarters (72%) of the landfilling option impacts arise from the transportation of waste to landfill, which results from the upstream production of fuel (52%) and vehicles used for collection (34%). Incineration with energy recovery meanwhile has water impacts more than 40 times higher than landfilling, linked to decarbonised water used during the incineration process. These impacts are however offset by the grid electricity avoided, with avoided impacts equivalent to more than double the water scarcity impacts of incineration.

[24] Waste disposal is modelled as municipal solid waste disposal (i.e. using default municipal solid waste characterization breakdown).

Likewise, RDF production and combustion has water impacts more than 75 times higher than landfilling, linked primarily to electricity consumed during the production process. These impacts are offset by the avoided fossil fuel production and consumption, with avoided impacts around a third (30%) greater than water scarcity impacts from RDF production and combustion. However, the net impacts remain higher than both the baseline scenario and incineration with energy recovery. Therefore, **in cases where plastics are not recyclable with current technologies (e.g. multi-layer plastics), incineration with energy recovery is the best option in terms of water scarcity impact**.

The recycling options have impacts higher than the baseline scenario; however, their net water scarcity impacts are dominated by the impacts avoided through virgin plastic offsetting. These avoided impacts are between eight and 14 times higher than impacts associated with transportation and recycling processing, resulting in net positive water scarcity impacts for all three recycling options. **The closed-loop recycling option results in the highest water scarcity benefit**.

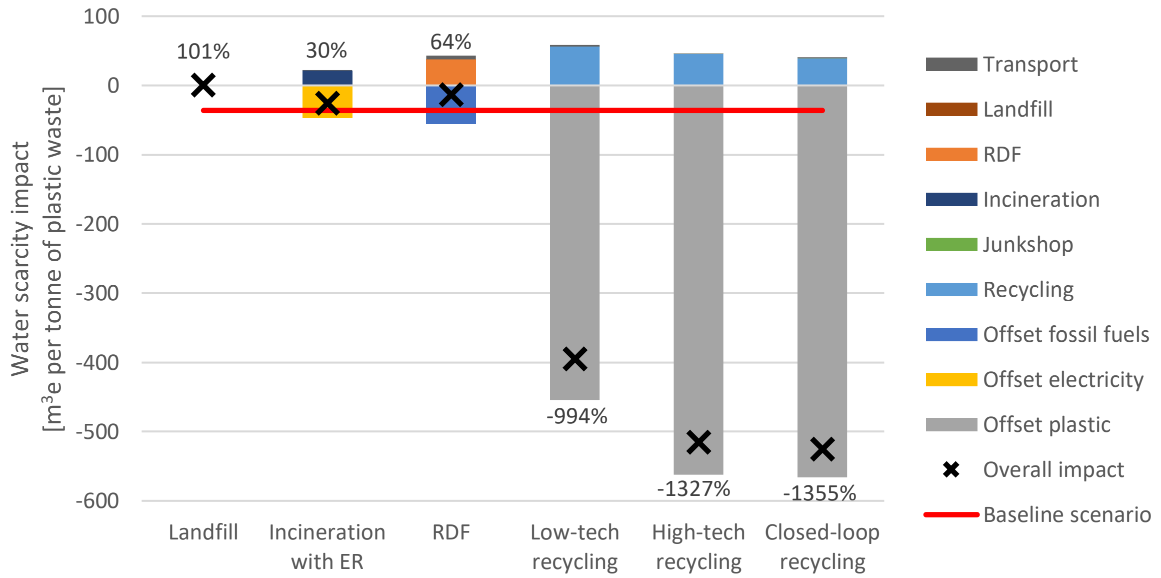

Figure 8: Water scarcity impacts, broken down by life cycle stage, for plastic waste management options in Cambodia. Crosses represent the net impacts each option, with percentages reflecting the difference in impact relative to the Cambodia baseline scenario for each option.

The impacts associated with the recycling value chain arise primarily from the recycling phase (>95%), resulting from water used in cleaning and processing, upstream production of electricity and upstream production of chemicals.

For low-technology recycling, as practiced by SMEs in Cambodia, over half (58%) of water impacts result from chemicals (sodium hydroxide, sodium chloride, formic acid and potassium aluminium sulphate), while around a third (32%) of impacts are from upstream production of electricity. Direct water use accounts for 6% of water impacts. Water impacts are therefore primarily linked to the cleaning of incoming plastic waste, which utilises the bulk of input water and chemicals (used to soften debris and assist removal) and therefore directly related to the "dirty" nature of incoming plastic waste. Cleaning requirements can be mitigated by obtaining cleaner plastic items, either through source separated collection or increased upstream pre-processing. Cleaner incoming plastic waste also has the added benefit of improving the quality of output recyclate. Energy efficiency measures, which reduce electricity consumption, will also assist in mitigating water scarcity impacts associated with the upstream generation of grid electricity.

For high technology and closed-loop recycling, around two-thirds (60% for high technology and 70% for closed-loop) of water impacts of water impacts are linked to upstream electricity generation, resulting from the increased level of mechanisation. Cleaning chemicals and direct water use account for between a quarter and a third of impacts. As with the low-technology recycling, the primary mitigation routes would be targeting cleaner plastic intake, to reduce cleaning demands, and energy efficiency, to reduce electricity consumption and the associated impacts. It is also possible that larger, mechanised plants could switch to renewable electricity sources, such as solar PV, which would effectively eliminate impacts from electricity consumption.

Avoided water scarcity impacts are split close to 50%:50% between PET and HDPE across all three recycling scenarios. Avoided PET has high impacts associated with input raw materials (terephthalic acid: 41%; ethylene glycol: 37%), as well as the water used during cleaning and processing (13%). Likewise, the avoided HDPE has high associated water scarcity impacts linked to the water use in processing (48%) and the ethylene feedstock (39%). Due to this, the avoided impacts are around an order of magnitude higher than the impacts associated with the recycling value chain. This results in the net negative water scarcity impacts for the recycling options.

4.2.3 Human health

Aggregated impact categories contributing to the human health AoP are shown in Figure 9, which, as with climate change impacts, are higher for incineration with energy recovery than the baseline scenario, while RDF production and the three recycling options have net negative human health impacts.

In the baseline scenario, the majority of human health impacts (88%) result from open burning (combustion) of plastic waste. These impacts arise from emissions to air (carbon dioxide accounting for 73%, with particulates and mercury accounting for approximately 10% and 8% respectively) and emissions to soil (heavy metals).

Incineration with energy recover is the only option investigated that increases the human health impacts of plastic waste management, linked to the carbon dioxide emitted during the combustion of carbon-rich plastic (98%) and water use in the upstream production of input chemicals, such as quicklime (11%). These emissions are not offset by the grid electricity avoided, with avoided emissions equivalent to only two-fifths (39%) of the human health impacts of incineration.

The landfilling, RDF production and three recycling options result in lower human health impacts than baseline plastic waste management. It may be noted that the human health impacts are dominated by impacts linked to short-term and long-term climate change impacts for the landfilling and recycling options (95% for landfilling and 87% for the three recycling options), meaning that the general impact trends, sources of impacts and mitigation options possible align with those discussed in the climate change impact section (Section 4.2.1), and are therefore not discussed in as much detail below.

The inert nature of plastic within landfill sites means that are few emissions to air and soil and therefore the human health impacts are low. In the case of RDF production and combustion, human health impacts are primarily associated with plastic RDF combustion (88% - primarily from carbon dioxide emissions) and electricity consumption for production (11%). These impacts are offset by the fossil fuels avoided, resulting in net negative human health impacts. Avoided impacts are linked primarily to fossil fuel combustion (86%), with upstream production only accounting for around a tenth (12%) of offset impacts. The offset combustion impacts are primarily linked to avoided greenhouse gas emissions from the combustion of carbon-rich fossil fuels (83%), particulate emissions (8%) and sulphur-based gases (6%). Particulate and sulphur-based emissions are a significant source of human health impacts from “dirty” fossil fuels, such as coal, and therefore avoided combustion through the use of plastic RDF, which burns cleaner and releases fewer emissions, has beneficial human health impacts on local communities. **In cases where plastics are not recyclable with current technologies (e.g. multi-layer plastics) therefore, RDF production is the best option in terms of human health impacts**.

The recycling options have impacts approximately equivalent to the baseline scenario; however, their net human health impacts are dominated by the impacts avoided through virgin plastic offsetting. These avoided emissions are between four and five times higher than impacts associated with transportation, sorting and recycling, resulting in a net positive effect on human health impacts for all three recycling options. **The closed-loop recycling option results in the highest human health benefit**.

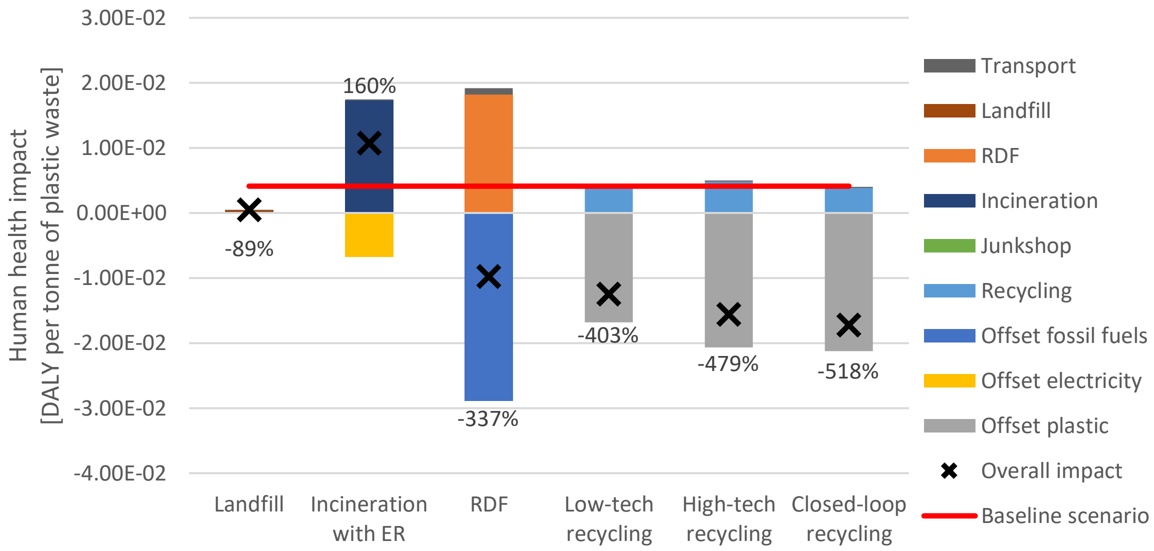

Figure 9: Human health impacts, broken down by life cycle stage, for plastic waste management options in Cambodia. Crosses represent the net impacts each option, with percentages reflecting the difference in impact relative to the Cambodia baseline scenario for each option.

The impacts associated with the recycling value chain arise primarily from the recycling phase, with impacts from junkshop operations (electricity consumption) and transportation of the material from junkshops to recyclers (diesel consumption in vehicles) accounting for less than 10% of impacts across all three options. Recycling phase impacts principally arise electricity consumption, heat generation and chemical consumption.

For low-technology recycling, as practiced by SMEs in Cambodia, three-quarters (73%) of human health impacts result from the use of electricity and fuels, while a fifth of impacts (16%) are from chemicals used in the process. Energy consumption should therefore be targeted to mitigate human health impacts from SME recycling. Chemicals are primarily used in the cleaning of incoming plastic waste and therefore directly related to the "dirty" nature of incoming plastic waste. Cleaning requirements can be mitigated by obtaining cleaner plastic items, either through source separated collection or increased upstream pre-processing.

For high technology and closed-loop recycling, around 90% of human health impacts are from the use of electricity and fuels, especially electricity from the increased level of mechanisation. As with the low-technology recycling, the primary mitigation route would be targeting energy efficiency to reduce consumption and the associated impacts. It is also possible that larger, mechanised plants could switch to renewable electricity sources, such as solar PV, which would minimise impacts from electricity consumption. Chemical consumption accounts for around 5% of impacts which is primarily used for cleaning operations and therefore linked to the quality of incoming plastic waste. Chemical consumption and associated impacts can be mitigated through the sourcing of cleaner plastic materials.

Avoided greenhouse gas emissions are split almost 50%:50% between PET and HDPE across all three recycling scenarios. Avoided PET has high impacts associated with input raw materials (terephthalic acid and ethylene glycol), as well as the heat and electricity inputs required for processing. Likewise, the avoided HDPE has high associated impacts linked to the ethylene feedstock and electricity and steam inputs required for processing. Due to this, the avoided impacts are significantly higher (390% for low-technology recycling to 530% for closed-loop recycling), than the impacts associated with the recycling value chain (collection, pre-processing and recycling). This results in the net negative human health impacts for the recycling options.

4.2.4 Ecosystem quality

Aggregated impact categories contributing to the ecosystem quality AoP are shown in Figure 10, which, as with climate change and human health impacts, are higher for incineration with energy recovery than the baseline scenario, while RDF production and the three recycling options have net negative ecosystem quality impacts.

In the baseline scenario, the majority of ecosystem quality impacts (90%) result from open burning (combustion) of plastic waste. These impacts arise from emissions to air (carbon dioxide accounting for 48%) and emissions to soil (heavy metals accounting for 47%).

Incineration with energy recover is the only option investigated that increases the ecosystem quality impacts of plastic waste management, linked to the carbon dioxide emitted during the combustion of carbon-rich plastic (99%). These emissions are not offset by the grid electricity avoided, with avoided emissions equivalent to only two-fifths (39%) of the ecosystem quality impacts of incineration.

The landfilling, RDF production and three recycling options result in lower ecosystem quality impacts than baseline plastic waste management. It may be noted that the ecosystem quality impacts are linked to short-term and long-term climate change impacts for the landfilling and recycling options (accounting for 64% and 54%-55% of total ecosystem quality impacts for landfilling and the three recycling options respectively), meaning that the general impact trends, sources of impacts and mitigation options possible align with those discussed in the climate change impact section (Section 4.2.1).

The inert nature of plastic within landfill sites means that are few emissions to air and soil and therefore the ecosystem quality impacts are low. Ecosystem quality impacts from RDF production and combustion are linked with plastic RDF combustion (87% - primarily from carbon dioxide emissions) and electricity consumption for production (11%). These impacts are more than offset by avoided fossil fuel production and combustion, resulting in net negative ecosystem quality impacts for RDF. The avoided direct combustion emissions contributing more than four-fifths (82%) of offset impacts, with upstream fossil fuel production accounting for a further fifth (17%) of offsets. Offset combustion impacts are linked to avoided greenhouse gas emissions from the combustion of carbon-rich fossil fuels (73%), as well as avoided heavy metal (10%) and sulphur-based gases (9%). Heavy metal and sulphur-based gas emissions, which result from the burning of “dirty” fossil fuels, such as coal, contribute to ecotoxicity and acidification impacts respectively. A such, **in cases where plastics are not recyclable with current technologies (e.g. multi-layer plastics) therefore, RDF production is the best option in terms of ecosystem quality impacts**.

The recycling options have impacts lower than the baseline scenario; however, their net ecosystem quality impacts are dominated by the impacts avoided through virgin plastic offsetting. These avoided emissions are between four and six times higher than impacts associated with transportation, sorting and recycling, resulting in a net positive effect on ecosystem quality impacts for all three recycling options. **The closed-loop recycling option results in the highest ecosystem quality benefit**.

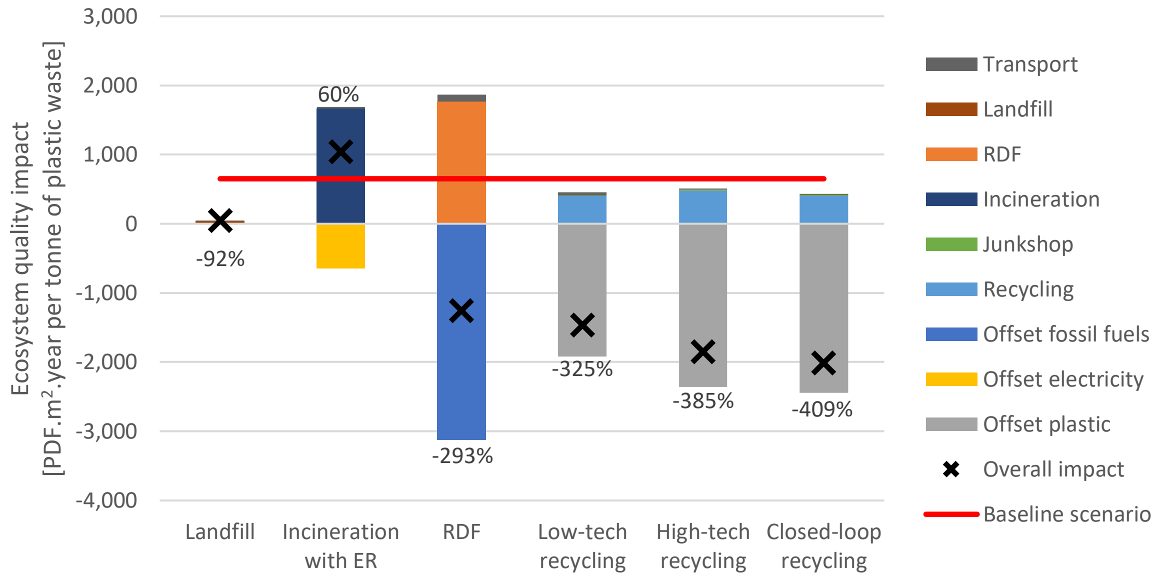

Figure 10: Ecosystem quality impacts, broken down by life cycle stage, for plastic waste management options in Cambodia. Crosses represent the net impacts each option, with percentages reflecting the difference in impact relative to the Cambodia baseline scenario for each option.

The impacts associated with the recycling value chain arise primarily from the recycling phase, with impacts from junkshop operations (electricity consumption) and transportation of the material from junkshops to recyclers (diesel consumption in vehicles) accounting for less than 13% of impacts across all three options. Recycling phase impacts principally arise electricity consumption, heat generation and chemical consumption.

For low-technology recycling, as practiced by SMEs in Cambodia, two-thirds (70%) of ecosystem quality impacts result from the use of electricity and fuels, while a fifth of impacts (18%) are from chemicals used in the process. Energy consumption should therefore be targeted to mitigate ecosystem quality impacts from SME recycling. Chemicals are primarily used in the cleaning of incoming plastic waste and therefore directly related to the “dirty” nature of incoming plastic waste. Cleaning requirements can be mitigated by obtaining cleaner plastic items, either through source separated collection or increased upstream pre-processing.

For high technology and closed-loop recycling, around 85% of ecosystem quality impacts are from the use of electricity and fuels, especially electricity from the increased level of mechanisation. As with the low-technology recycling, the primary mitigation route would be targeting energy efficiency to reduce consumption and the associated impacts. It is also possible that larger, mechanised plants could switch to renewable electricity sources, such as solar PV, which would minimise impacts from electricity consumption. Chemical consumption is the second largest impact source (around 5%-6%), which is primarily used for cleaning operations and therefore linked to the quality of incoming plastic waste. Chemical consumption and associated impacts can be mitigated through the sourcing of cleaner plastic materials.

Avoided greenhouse gas emissions are split almost 50%:50% between PET and HDPE across all three recycling scenarios. Avoided PET has high impacts associated with input raw materials (terephthalic acid and ethylene glycol), as well as the heat and electricity inputs required for processing. Likewise, the avoided HDPE has high associated impacts linked to the ethylene feedstock and electricity and steam inputs required for processing. Due to this, the avoided impacts are significantly higher (420% for low-technology recycling to 570% for closed-loop recycling), than the impacts associated with the recycling value chain (collection, pre-processing and recycling). This results in the net negative ecosystem quality impacts for the recycling options.

4.2.5 Fossil energy use

Figure 11 shows that fossil and nuclear energy use impacts, used here as a proxy for non-renewable resource depletion as the AoP is not yet quantified, are higher for landfilling than the baseline scenario, while incineration with energy recovery and the three recycling options have net negative fossil energy use impacts.

In the baseline scenario, fossil energy impacts are primarily from recycling processing (79%), even with the small fraction of plastic waste sent for recycling, and transportation of plastic waste to incineration, landfill and recyclers (15%). This impact results from direct (fuel consumption on-site and in vehicles) and indirect (electricity, where fossil energy used in upstream generation) energy consumption. These impacts are more than offset by avoided virgin plastic production, resulting in the baseline scenario having a net negative fossil energy use impact.

Landfilling is the only option investigated that increases the fossil energy use impacts of plastic waste management, linked to the diesel used in waste transportation (61%) and for landfill operations (39%).

The incineration with energy recovery and three recycling options result in lower fossil energy use impacts than baseline plastic waste management, due to the impacts avoided through grid electricity and virgin plastic offsetting.

Incineration with energy recovery has fossil energy use impacts associated with diesel used for transportation of waste to incineration (35%) and fuel required for the incineration process (start-up fuel etc. – 26%), with remaining impacts primarily associated with chemical inputs and facility construction. These impacts are more than offset by the grid electricity generation avoided, which saves on coal (half of Cambodia's electricity generation) and other fossil fuels (7% of generation). Likewise, RDF production and combustion has fossil energy use impacts associated with diesel used for transportation (34%) and electricity required for production (55%). These impacts are more than offset by the fossil fuel consumption avoided. Therefore, **in cases where plastics are not recyclable with current technologies (e.g. multi-layer plastics), RDF production is the best option in terms of fossil energy use impacts**.

The recycling options have impacts higher than the baseline scenario; however, their net fossil energy use impacts are dominated by the impacts avoided through virgin plastic offsetting. These avoided emissions are between ten and 15 times higher than impacts associated with transportation, sorting and recycling, resulting in a net positive effect on fossil energy use impacts for all three recycling options. **The closed-loop recycling option results in the highest fossil energy use benefit**.

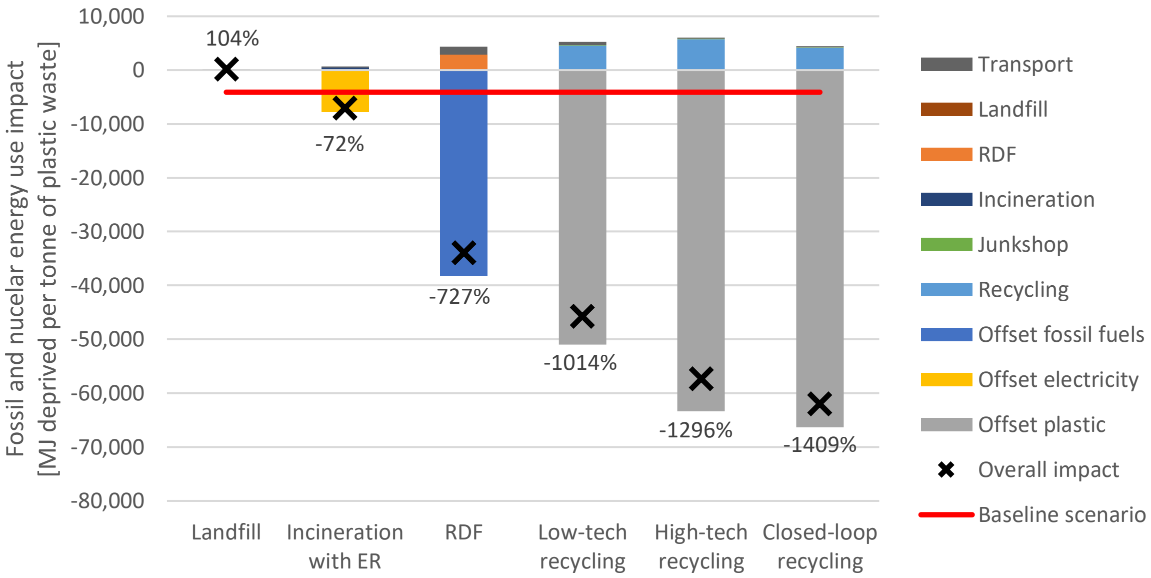

Figure 11: Fossil and nuclear energy use impacts, broken down by life cycle stage, for plastic waste management options in Cambodia. Crosses represent the net impacts each option, with percentages reflecting the difference in impact relative to the Cambodia baseline scenario for each option.

The impacts associated with the recycling value chain arise primarily from the recycling phase, with impacts from junkshop operations (electricity consumption) and transportation of the material from junkshops to recyclers (diesel consumption in vehicles) accounting for less than 13% of impacts across all three options. Recycling phase impacts principally arise electricity consumption, heat generation and chemical consumption.

For low-technology recycling, as practiced by SMEs in Cambodia, four-fifths (79%) of ecosystem quality impacts result from the use of electricity and fuels, while a fifth of impacts (19%) are from chemicals used in the process. Energy consumption should therefore be targeted to mitigate fossil energy use impacts from SME recycling. Chemicals are primarily used in the cleaning of incoming plastic waste and therefore directly related to the “dirty” nature of incoming plastic waste. Cleaning requirements can be mitigated by obtaining cleaner plastic items, either through source separated collection or increased upstream pre-processing.

For high technology and closed-loop recycling, more than 90% of impacts are from electricity consumption and fuel use, especially electricity from the increased level of mechanisation. Energy related impacts can be mitigated through energy efficiency measures, which reduce consumption and the associated fossil energy use impacts. It is also possible that larger, mechanised plants could switch to renewable electricity sources, such as solar PV, which would effectively eliminate impacts from electricity consumption.

Avoided greenhouse gas emissions are split almost 50%:50% between PET and HDPE across all three recycling scenarios. Avoided PET has high impacts associated with input raw materials (terephthalic acid and ethylene glycol) as these are derived from fossil resources, as well as the heat and electricity inputs required for processing. Likewise, the avoided HDPE has high associated impacts linked to the ethylene feedstock (derived from crude oil and natural gas) and electricity and steam inputs required for processing. Due to this, the avoided impacts are significantly higher (960% for low-technology recycling to 1,500% for closed-loop recycling), than the impacts associated with the recycling value chain (collection, pre-processing and recycling). This results in the net negative fossil energy use impacts for the recycling options.

4.2.6 Plastic and circularity impacts

The plastic footprint and MCI results for the six waste management options are presented in Table 17.

Incineration with energy recovery, RDF production and the three recycling options result in a plastic footprint of 0, as these waste management options effectively manage plastic waste. However, landfilling results in a plastic footprint higher than the baseline scenario due to landfills in Cambodia being poorly managed, meaning that plastic waste can easily escape landfill sites and enter the natural environment. This issue can be addressed by ensure that landfills are effectively managed (e.g. waste is compacted and covered with cover material daily), preventing plastic from blowing away or otherwise escaping the landfills.

The material circularity indicator (MCI) provides a quantitative assessment of the circularity of a system, varying from 0 for a linear system (i.e. virgin input, use and disposal) to 1 for a fully circular system (i.e. 100% recycled input, use and 100% recycling, with no material lost during recycling)[25]. In this case, three values are presented:

- **Linear Flow Index (LFI)**: Measure of the percentage of material flowing in a linear manner, this includes the fraction of feedstock from virgin sources and the fraction of material sent for disposal[26] at end-of-life.
- **Material Flow Indicator (MCI)**: Measure of the circularity of system, this is calculated from the LFI.
- **Percentage of maximum MCI**: As the MCI is based on the entire plastic system (i.e. including plastic inputs into products), it does not match the "gate-to-grave" system boundary of this LCA study. When considering, virgin plastic inputs, the maximum achievable MCI is 45%. To align with the "gate-to-grave" system boundary of the LCA, the percentage of this maximum MCI is reported and used for analysis.

Landfilling, incineration with energy recovery and RDF production therefore have an MCI and percentage of maximum MCI of 0, as the waste management option is fully linear. **The three recycling options have a percentage of maximum MCI around 90%, showing the circular nature of recycling as a waste management option**. The slight differences in MCI values between the recycling options is due to differing recycling yields (efficiencies). It should be noted that in the MCI methodology all recyclate, irrespective of quality, has the same value (i.e. quality ratios are not considered).

Table 17: Summary of plastic footprint and material circularity indicator (MCI) for the plastic waste management options in Cambodia

Waste management option	Plastic footprint	Material Circularity Indicator (MCI)		
	Plastic leaked to the marine environment	LFI	MCI[27]	Percentage of maximum MCI
Baseline scenario	6.4%	96%	3%	7%
Landfill	10.0%	100%	0%	0%
Incineration with energy recovery	0%	100%	0%	0%
RDF production	0%	100%	0%	0%
Low-technology recycling	0%	54%	39%	86%
High technology recycling	0%	55%	40%	90%
Closed-loop recycling	0%	55%	41%	91%

4.3 Data quality and uncertainty considerations

It is the nature of any LCA study that some data points are uncertain, which translates into uncertainty in the impact assessment results and associated interpretation. This is particularly the case in this LCA study, where data was sourced almost exclusively from secondary data sources, with primary data collection only providing data on recycling transport distances, recycling yields and selected recycling process inputs (electricity, potassium aluminium sulphate and sodium hydroxide). This results in data that may be out-of-date, not geographically representative (or geographically representative of only regions within Cambodia) and/or not technologically (process) representative. The lack of data in certain cases also meant that various assumptions (e.g. PET and

[25] In practice an MCI of 1 is not achievable, as there will always be a degree of wastage from the recycling process.
[26] Incineration with energy recovery is considered disposal according to the MCI methodology, as the material and associated value of the waste is lost from the system. It is therefore not considered part of a true circular economy.
[27] Based on an assumed Utility of 1, meaning that the recyclate is used for typical production (i.e. products that do not have increased lifespan or number of uses).

HDPE being the main polymers recycled) had to be made in the modelling process. The reliability and completeness of the data used for modelling therefore impacts the certainty of reported values and associated conclusions on the preferred plastic waste management option.

As such, sensitivity analyses are performed around some of the key data points and assumptions to test the LCA results and conclusions presented above.

4.3.1 Transportation distances

Transportation distances to landfill, incineration and recyclers are unknown and may vary considerably depending on region and type of waste management option chosen. For example, transportation is likely to be much higher for any plastic collected in rural regions and likewise transportation distances are likely to be greater for more complex, capital intensive systems (e.g. incineration with energy recovery and closed-loop recycling), which need to be implemented on a larger scale and therefore would only be constructed in a few select locations within a country.

Transportation impacts are minor for all impact categories and management options, except for landfilling where it accounts for a meaningful share of impacts (14% for aggregated human health and ecosystem quality impacts; 61% for fossil energy use impacts).

The negligible nature of transportation impacts means that even if transportation distances were increased ten-fold from the default (secondary data) value (i.e. to 510 kilometres for delivery to incineration and recyclers, which is approximately four times the average distance reported by Cambodian recyclers), the impacts of transportation would still only be around 11%-13% of aggregated human health and ecosystem quality impacts. If transportation was increased likewise for landfilling (i.e. 240 km), transportation impacts would account for 62% of aggregated human health and ecosystem quality impacts. It is however, extremely unlikely that waste would be transported such distances for disposal.

These impacts do not change the overall conclusions, with the three recycling options having the lowest impacts irrespective of transportation distance and closed-loop recycling remaining the slightly most preferable option. RDF also remains the most preferable option for non-recyclable plastics.

4.3.2 Polymers recycled

The current LCA model assumes that only PET and HDPE are recycled and that the split between these two polymers is 50%:50%, both of which are uncertain.

Primary and secondary data suggests that LDPE, PP, PS and PVC[28] may also be recycled within Cambodia (Aryan et al., 2019; Hashmi et al., 2023; iDE, 2024; Majeed et al., 2018; Seng et al., 2018), which could influence the impacts associated with both the recycling process and offset (avoided) virgin plastic production.

The life cycle environmental impacts of different virgin plastic polymers are presented in Figure 12. Overall PVC has the lowest short-term climate change and aggregated human health and ecosystem quality ("single-score") impacts. However, PVC is not investigated further, as PVC recycling is extremely limited globally and unlikely to be practiced on a significant scale within Cambodia. Of the other polymers commonly recycled, HDPE has the lowest climate and "single-score" impacts, along with the second lowest fossil energy use impact (5% higher than PET, which has the lowest fossil energy use impact). As such, scenarios are investigated where offset virgin plastic

[28] PVC recycling is deemed unlikely, as PVC is not commonly recycled anywhere in the world. It is therefore assumed that these PVC plastics are rather re-used.

production is solely HDPE, to understand the “worst case scenario” (i.e. when offset life cycle impacts are the lowest).

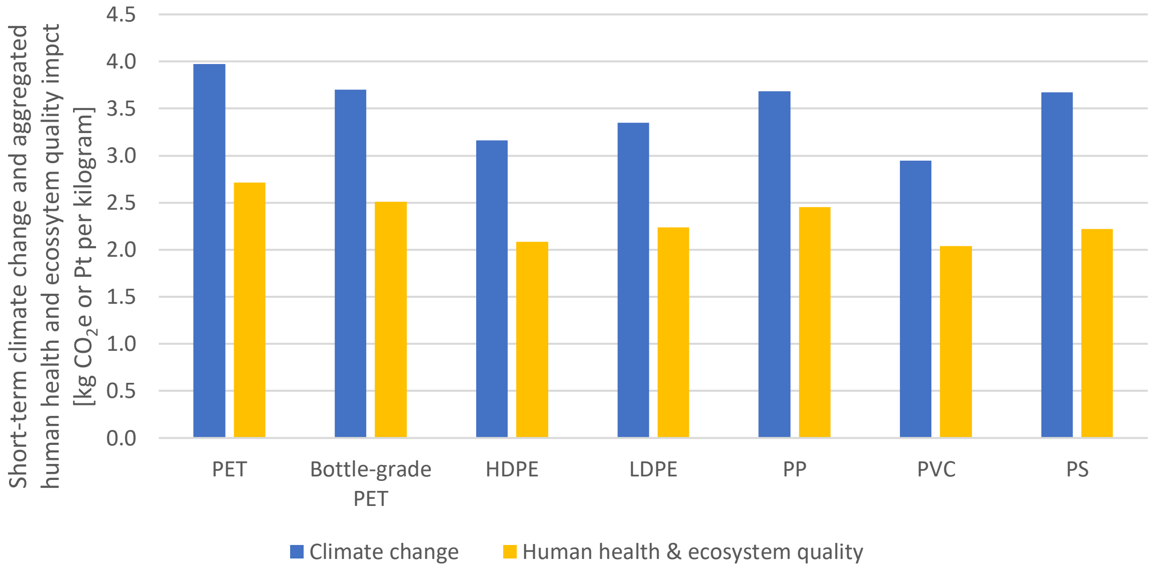

Figure 12: Short-term climate change and aggregated human health & ecosystem quality impacts of various virgin plastic polymers[29]

Low-technology mechanical recycling was modelled using Asian recycling data that covered mixed polymer recycling (i.e. recycling of various polymer types) and therefore is representative of SME recycling, irrespective of the polymers recycled. However, high technology and closed-loop recycling was modelled specifically from the PET and HDPE recycling datasets contained within ecoinvent. Previous LCA studies (Franklin Associates, 2018, 2011), as well as life cycle databases (ecoinvent and Sphera) suggest that PET recycling is the most input intensive and results in the greatest life cycle environmental impacts[30]. As such, scenarios are investigated where high technology and closed-loop recycling are based solely on PET recycling, to understand the “worst case scenario” (i.e. when inputs to and life cycle environmental impacts associated with the recycling process are the highest).

The results of this “worst case scenario”, where the high-technology and closed-loop recycling is based on PET recycling but offsetting virgin HDPE production, are presented in Figure 13 (climate change impact) and Figure 14 (aggregated human health and ecosystem quality impact). This analysis reveals that even in the case when the impacts of the recycling process are maximised and the offsets from avoided virgin plastic production are minimised, the three recycling options still have the best environmental impacts and are the preferred option for plastic waste management. This trend is also seen for non-renewable resource depletion impacts.

At this “worst case”, the environmental impacts of low-technology recycling and RDF production are almost equivalent; however, even here, the low-technology recycling has fractionally better environmental impacts. It is also unlikely for this “worst case” to play out in the real world, as recycling inputs are somewhat linked to virgin production inputs, through polymer characteristics such as melting point temperature (i.e. polymers that have lower avoided virgin polymer impacts, such as HDPE, should have lower recycling inputs and associated impacts, as less energy is required to melt the polymer and form recyclate).

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[29] Suspension polymerized PVC

[30] No reliable studies or life cycle datasets are available on PVC recycling, as it is not commonly undertaken currently. As such, these comparisons are based on PET, PE and PP.

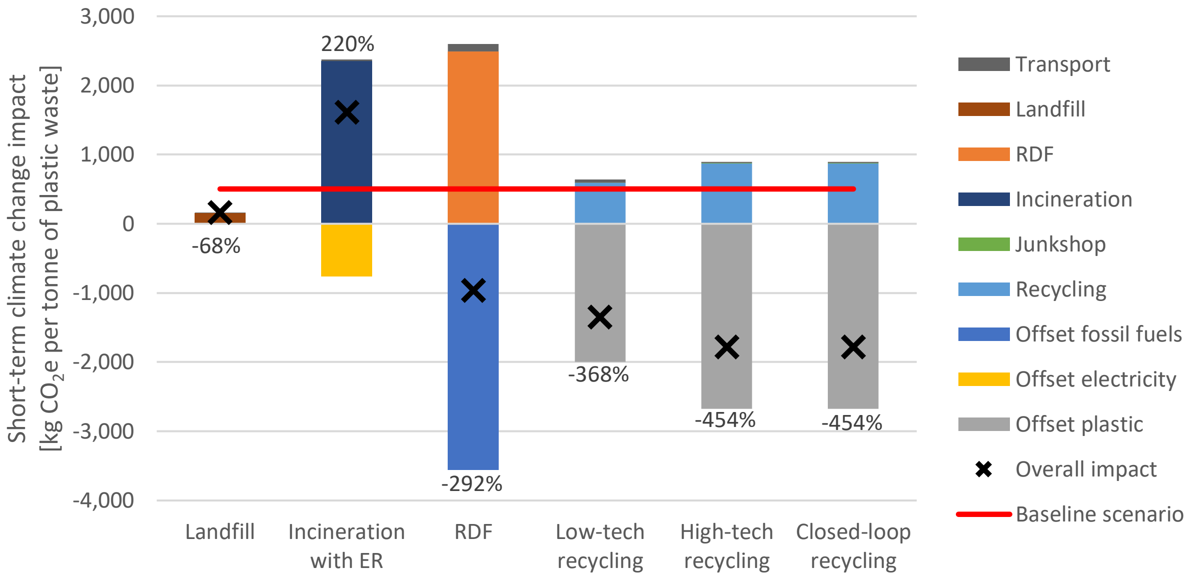

Figure 13: Short-term climate change impacts, broken down by life cycle stage, for plastic waste management options in Cambodia. Scenario investigating the "worst case" scenario for polymers (PET recycling, offsetting HDPE virgin polymer).

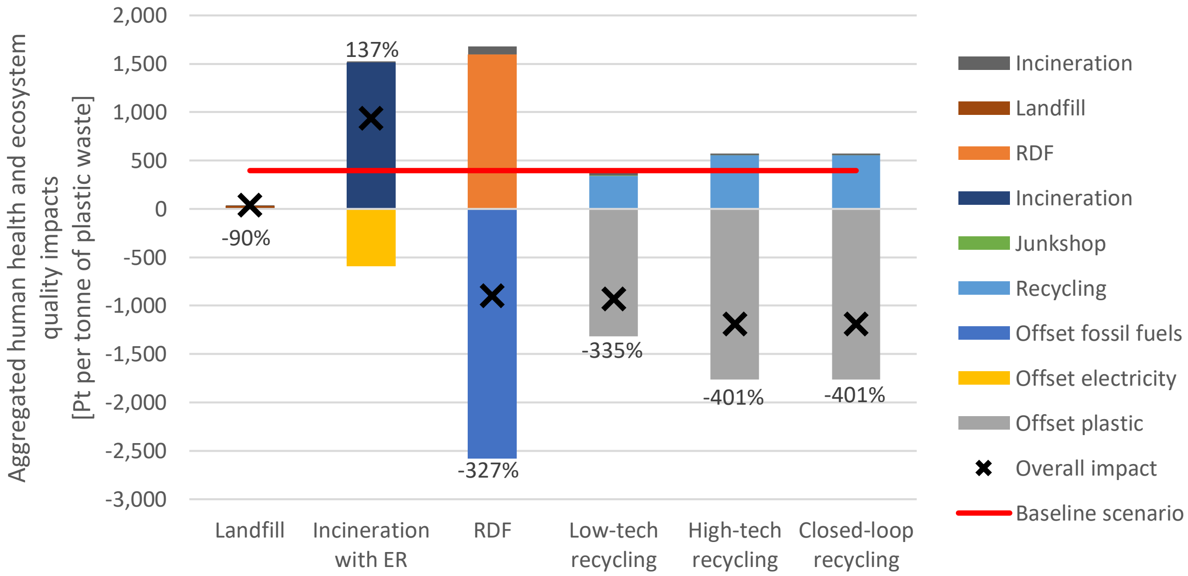

Figure 14: Aggregated life cycle human health and ecosystem quality impacts, broken down by life cycle stage, for plastic waste management options in Cambodia. Scenario investigating the "worst case" scenario for polymers (PET recycling, offsetting HDPE virgin polymer).

4.3.3 Low-technology recycling yield

Recycling yields vary greatly depending on the quality of incoming plastic waste (i.e. the mass of other plastics and debris in the plastic waste, how much organic matter is attached to the plastic and how damaged the plastic is from sun, water and chemicals), cleaning processes utilised and the desired quality of the output recyclate. Primary and secondary data reveals that yields for low-technology recycling can be as low as 75% or as high as 97%. Secondary data suggested that yields below 80%[31] are unlikely and therefore the 75% suggested by some recyclers

[31] Aligns with the yields in the ecoinvent PET recycling dataset.

in Cambodia may be erroneous or may include other co-processed streams (e.g. glass and metal sent to other recyclers). Due to this uncertainty, the effect of process yield is tested with sensitivity analysis. This yield influences input intensity (inputs per kilogram of recyclate) but also directly influences the amount of waste generated from the recycling process.

The results of this scenario analysis are presented in Figure 15 (climate change impact) and Figure 16 (aggregated human health and ecosystem quality impact). This analysis reveals that irrespective of the yield considered, the low-technology recycling option has better life cycle environmental impacts than the baseline scenario, landfilling, incineration with energy recovery or RDF production.

It may be noted that if yields approach 9%, the low-technology recycling option has better "single-score" impacts (i.e. aggregated human health and ecosystem quality impacts) than high technology recycling, while if yield reach the maximum reported value of 97%, the low-technology option comes close to matching closed-loop recycling in terms of environmental benefits. This demonstrates that processing yields are key to improving process sustainability and the overall benefits of the recycling process.

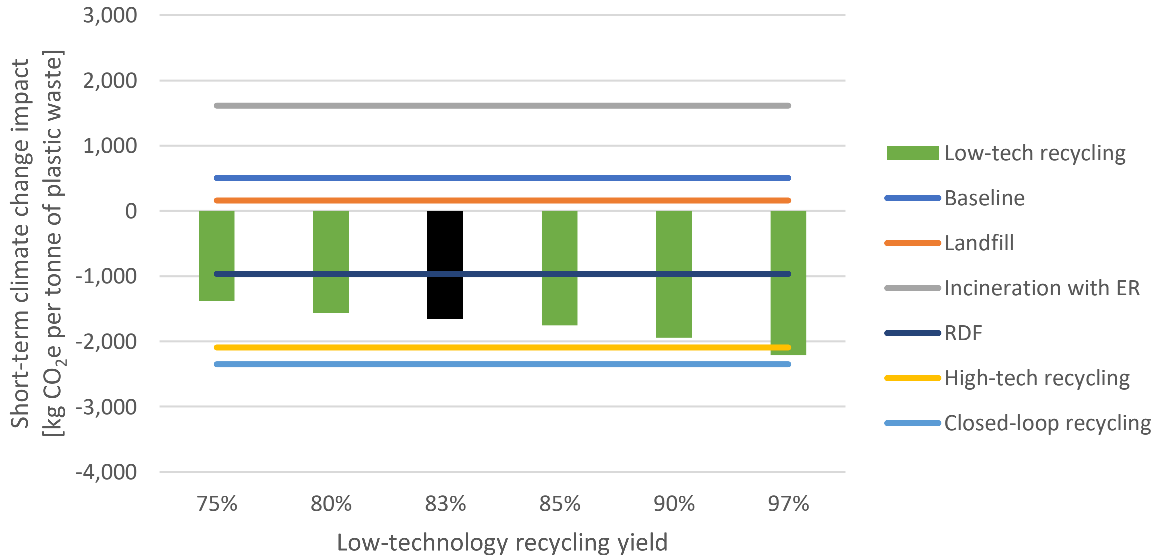

Figure 15: Short-term climate change impacts for scenario investigating varying the recycling yield on low-technology mechanical recycling. Black column is default low-technology mechanical recycling scenario (yield of 82.5%).

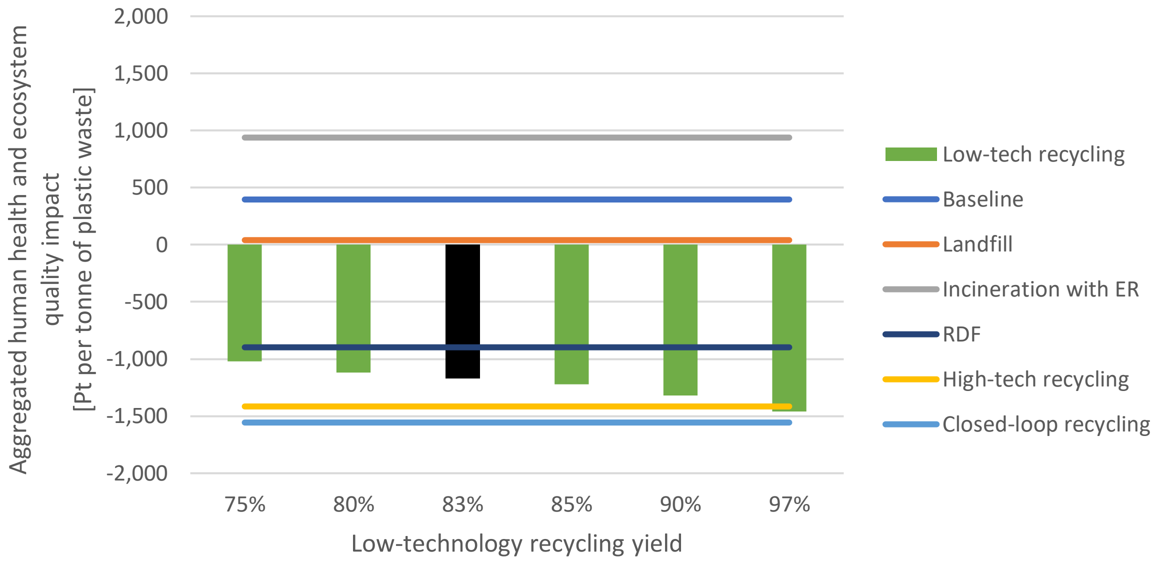

Figure 16: Aggregated human health and ecosystem quality impacts for scenario investigating varying the recycling yield on low-technology mechanical recycling. Black column is default low-technology mechanical recycling scenario (yield of 82.5%).

4.3.4 Low-technology energy inputs

Energy demands for recycling vary depending on the level of mechanisation, as well as the quality of incoming plastic (e.g. now much cleaning is required) and the desired quality of the recyclate (e.g. additional vacuum extraction systems may be required to remove all impurities for food-grade recyclate production). The energy demands for the three recycling options are summarised in Table 18, which shows that energy inputs for PET recycling can be as high as 11.4 MJ per kilogram of plastic waste processed. The primary electricity consumption data from Cambodian SME recyclers, combined with secondary data on fuel inputs, showed overall energy demands of 1.8 MJ per kilogram of plastic waste processed, which is greater than the highest reported energy demands for low-technology mechanical recycling of 1.5 MJ/kg (Majeed et al., 2018). The energy input for low-technology recycling is therefore tested with sensitivity analysis.

Table 18: Energy inputs into recycling options

	Low-technology recycling	High technology recycling	Closed-loop recycling
Electricity [kWh/kg plastic waste]	0.394[32]	HDPE: 0.490 PET: 0.935	HDPE: 0.490 PET: 0.343
Heat [MJ/kg plastic waste]	0.388	HDPE: 0.278 PET: 7.99	HDPE: 0.278 PET: 2.57
Total [MJ/kg plastic waste]	1.81	HDPE: 2.04 PET: 11.36	HDPE: 2.04 PET: 3.80

The results of this scenario analysis are presented in Figure 17 (climate change impact) and Figure 18 (aggregated human health and ecosystem quality impact). This analysis reveals that irrespective of the energy inputs considered, the low-technology recycling option has better life cycle environmental impacts than the baseline scenario, landfilling or incineration with energy recovery. The low-technology recycling option also has better life cycle environmental impacts than RDF production unless energy consumption is greater than the closed-loop PET recycling value of 3.8 MJ/kg.

[32] Secondary data suggested a value of 0.181 kWh/kg plastic waste, resulting in a total energy demand of 1.04 MJ/kg plastic waste.

When energy inputs for low-technology recycling are low (i.e. from 1 MJ/kg up to 1.8 MJ/kg, the Cambodian primary data value), the overall benefits of low-technology recycling are within 25% of high technology and closed-loop recycling. If energy inputs reach the levels seen for high technology HDPE recycling (2 MJ/kg), then the aggregated "single-score" benefits of low-technology recycling are 19% and 26% lower than high technology and closed-loop recycling respectively. This trend continues, with low-technology recycling benefits around a third lower than other recycling options if the closed-loop PET recycling energy inputs of 3.8 MJ/kg are considered.

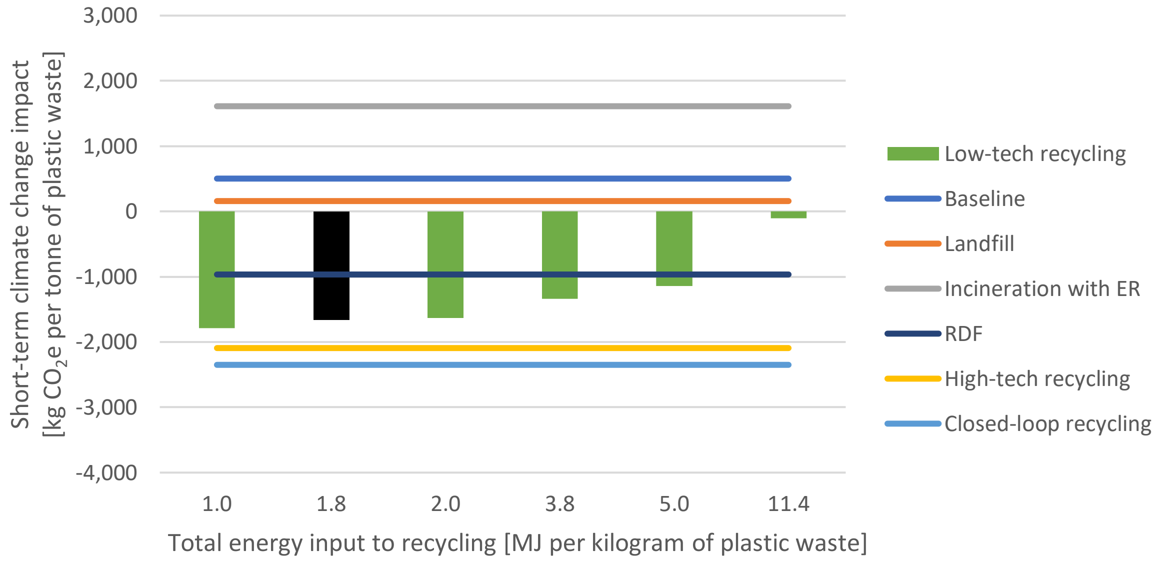

Figure 17: Short-term climate change impacts for scenario investigating varying the energy input for low-technology mechanical recycling. Black column is default low-technology mechanical recycling scenario (1.8 MJ/kg).

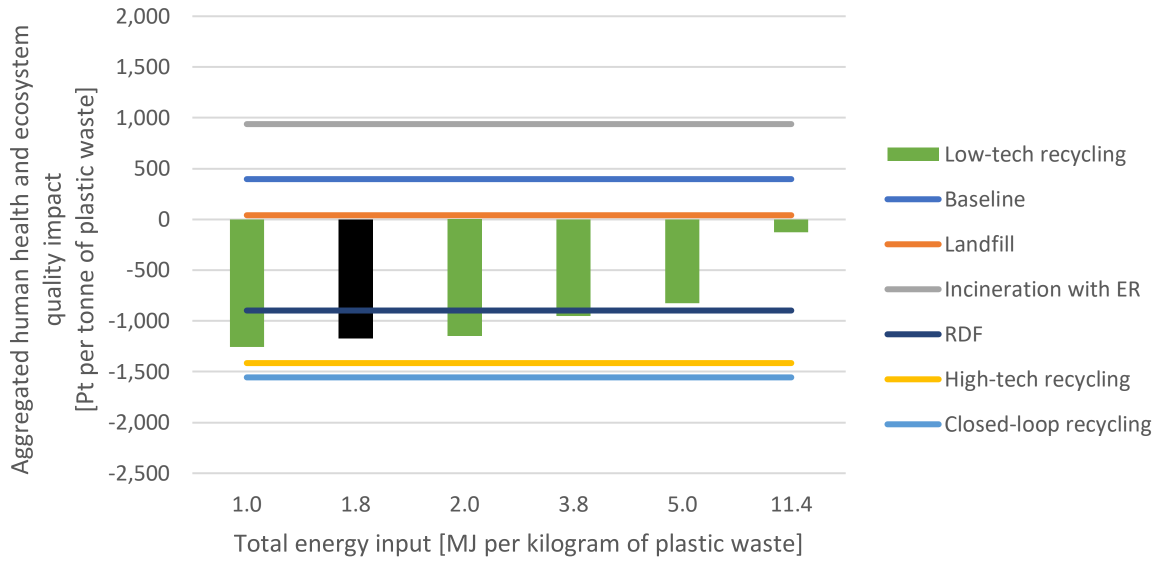

Figure 18: Aggregated human health and ecosystem quality impacts for scenario investigating varying the energy input for low-technology mechanical recycling. Black column is default low-technology mechanical recycling scenario (1.8 MJ/kg).

4.3.5 Recyclate quality ratios

Recycling quality ratios depend on quality of output recyclate and therefore are linked to the quality of incoming plastic waste, cleaning processes employed and the recycling process itself. The applicable quality ratio to apply within a study also depends on the final application of the recyclate, as certain applications can handle lower quality plastic inputs and therefore even lower quality recyclate directly replaces virgin plastic. For example, in the case of plastic film or bottle production, any contamination in the recyclate results in defective film or bottles, leading to high process losses and even machinery breakdowns. In these cases, a large mass of recyclate is required to fulfil the same role as a kilogram of virgin plastic, which should be contamination free. However, in the case of plastic irrigation pipes, which have a thick wall, some contamination can be accommodated without causing pipe defects. In this case, an equivalent mass of recyclate is required to fulfil the same role as a kilogram of virgin plastic. Secondary data reveals that assumed quality ratios can be as low as 0.5 (PLACES, 2023), while the CFF default for mechanical recycling is 0.9 (Table 12). The quality ratio for low-technology recycling is therefore tested with sensitivity analysis.

The results of this scenario analysis are presented in Figure 19 (climate change impact) and Figure 20 (aggregated human health and ecosystem quality impact). This analysis reveals that irrespective of the quality ratio considered, the low-technology recycling option has better life cycle environmental impacts than the baseline scenario, landfilling or incineration with energy recovery. The low-technology recycling option also has better life cycle environmental impacts than RDF production unless the quality ratio is below two-thirds (67%). This quality ratio would only be applicable if the recyclate is poor quality and could only be utilised for “downcycling”, such as the production of plastic bricks and furniture. Based on discussions with recyclers in Cambodia, this is not the case, with recyclate being used for high-quality applications and therefore such a low quality ratio is not deemed applicable even in the case of low-technology recycling.

It may be noted that quality ratios of 0.9 or above are used, as suggested by the CFF default values, the low-technology recycling option has better “single-score” impacts (i.e. aggregated human health and ecosystem quality impacts) than high technology. Similarly, at quality ratios of 0.95 or above, low-technology recycling has “single-score” impacts better than closed-loop recycling. This demonstrates that the quality of output recyclate is key to improving process sustainability and the overall benefits of the recycling process. The output quality is linked to the input quality (cleanliness etc.) of the plastic waste input.

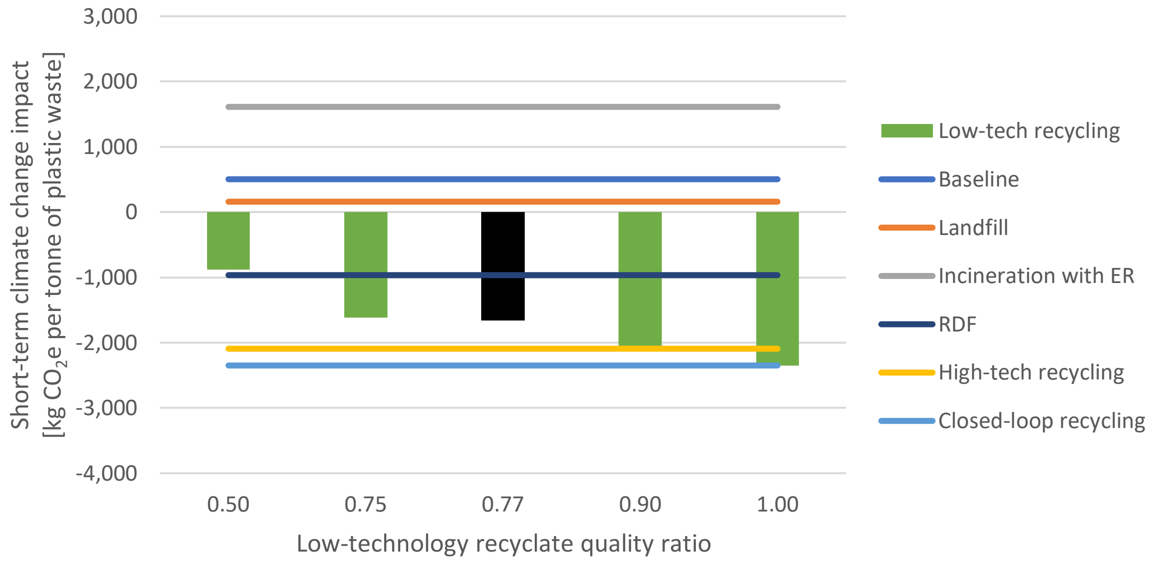

Figure 19: Short-term climate change impacts for scenario investigating varying the quality ratio of recyclate from low-technology mechanical recycling. Black column is default low-technology mechanical recycling scenario (quality ratio of 0.77).

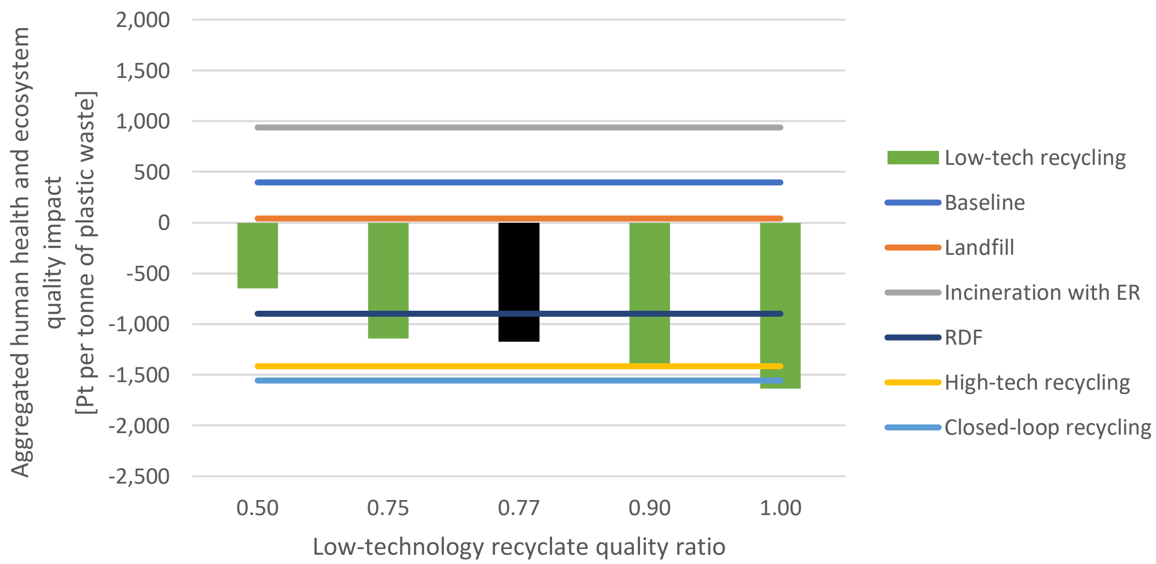

Figure 20: Aggregated human health and ecosystem quality impacts for scenario investigating varying the quality ratio of recyclate from low-technology mechanical recycling. Black column is default low-technology mechanical recycling scenario (quality ratio of 0.77).

4.3.6 End-of-life allocation

The results are presented by applying system expansion, as recommended by the LCA ISO standards to avoid allocation at end-of-life. However, many LCA studies are conducted by applying cut-off (recycled content) allocation, which dictates that the impacts of waste disposal and/or recycling are "cut off" once waste is disposed of and/or has reached the facility where it will be recycled. This means that for recycling, processes - and their burdens - are only considered in the plastic waste life cycle up to the point that the plastic waste is delivered to recyclers. The processing required to produce the recyclate and any avoided virgin plastic associated with the use of the recyclate is not considered with cut-off allocation. Thus with cut-off, the only benefit is the avoided disposal (in this case the baseline scenario), and the only impacts of recycling are the transport of the material to the point of recycling.

The study results, using cut-off allocation are presented in Figure 21 (climate change impact) and Figure 22 (aggregated human health and ecosystem quality impact). Even with the change in allocation approach, the recycling options show the best life cycle environmental impacts. For non-recyclable plastics, RDF production has impacts lower than either the baseline scenario, landfilling or incineration with energy recovery.

It may be noted that with cut-off allocation all the recycling options have the same impacts, as the recycling processes themselves, as well as the avoided impacts from virgin plastic offsetting are not considered.

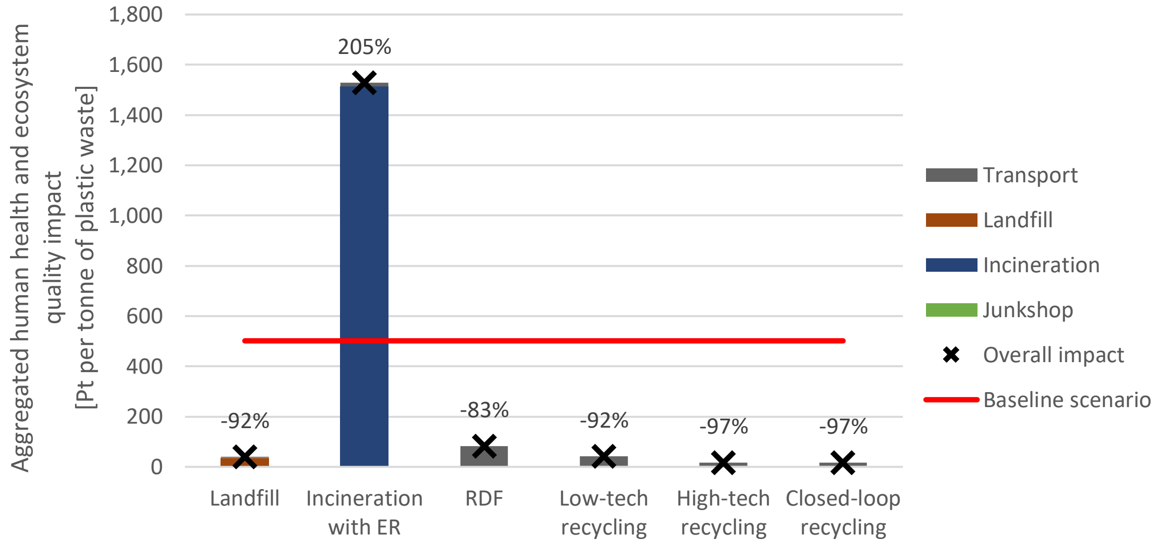

Figure 21: Short-term climate change impacts, broken down by life cycle stage, for plastic waste management options in Cambodia. Results presented according to cut-off allocation.

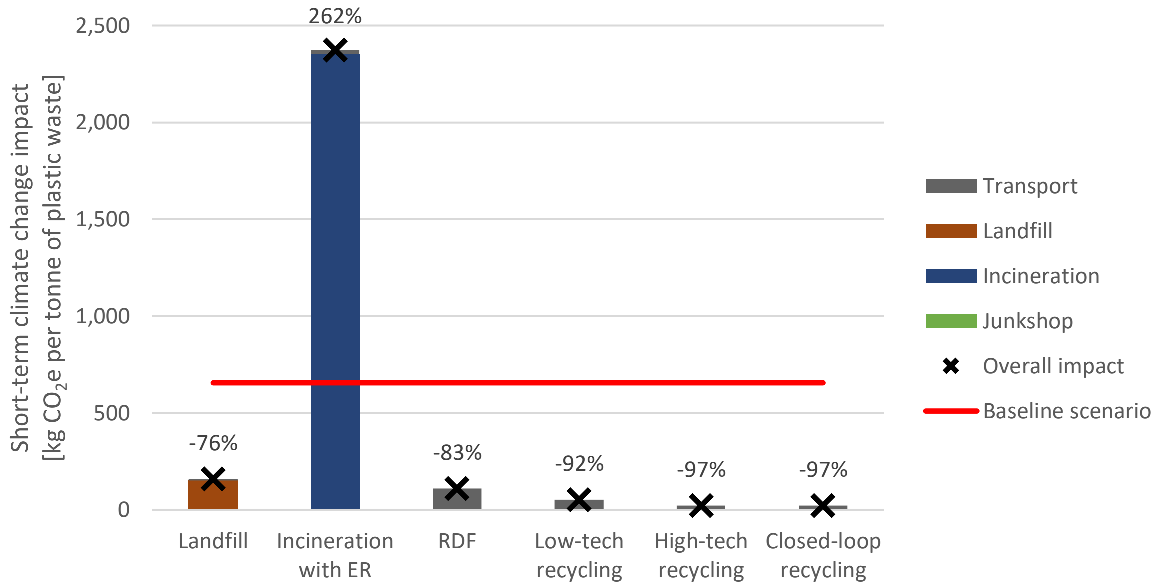

Figure 22: Aggregated human health and ecosystem quality impacts, broken down by life cycle stage, for plastic waste management options in Cambodia. Results presented according to cut-off allocation.

The cut-off approach reflects the least benefits to the producer of recycled materials, and system expansion the most benefits. The European Commissions Circular Footprint Formula (CFF) represents a compromise between the two, with benefits shared between the producer and the user of recycled materials. The overall results of the study using CFF allocation will therefore sit between the system expansion and cut-off results, indicating that again the recycling options will present the most beneficial life cycle impacts.

5 Conclusions

Plastic waste management in Cambodia is relatively informal, with plastic generally being landfilled, openly dumped or openly burnt. **Open burning especially has significant human health and ecosystem quality impacts**, due to the release of greenhouse gases and other emissions to air and soil. Alongside these impacts, the **plastic is "wasted" and lost from the economy**, losing a resource that can be used to used to avoid virgin plastic production. Furthermore, the landfilled and openly dumped plastic waste has the potential to enter water system and flow into the ocean, furthering global plastic and microplastic issues.

The ISO 14044:2006 Standard states that wherever possible allocation should be avoided through the use of system expansion. As such, **system expansion is deemed the most appropriate approach** for identifying the environmentally preferred end-of-life management option for plastic waste and is used in this LCA study to fully account for the benefits of sending plastic waste for recycling or energy recovery.

The LCA results demonstrate that diverting plastic waste from landfills, open dumps and, especially, open burning has substantial environmental benefits. By **avoiding disposal impacts and producing recyclate, which avoids the production of virgin plastic, all three recycling options considered significantly reduce the life cycle impacts of plastic waste management**. These lower impacts are seen across all life cycle environmental impact categories, including climate change, human health, ecosystem quality and non-renewable resource depletion impacts. Alongside this, the recycling options align with **circular-economy principals** and ensure the value of plastics are not lost from the economy, as well as ensuring **less plastic enters the nature environment and water systems**. The LCA findings are robust with respect to transport distances, polymers recycled, the quality of recyclate produced (quality ratios), recycling energy inputs and recycling yields, as well as the allocation approach followed (cut-off, CFF or system expansion). Nonetheless, end-of-life allocation does affect the extent of the reduction in environmental impacts relative to the baseline scenario.

In cases where **plastics cannot be recycled** currently (e.g. multilayers), the LCA demonstrates that **RDF production is the preferred management option**. RDF production has lower human health and ecosystem quality impacts, as well as non-renewable resource depletion impacts, than the baseline scenario, landfilling or incineration with energy recovery, although it has worse water scarcity impacts[33]. The magnitude of reductions in human health and ecosystem quality impacts however indicates that RDF production is overall the preferrable option. The LCA results in this case are also robust in respect to allocation approach followed. The RDF production option however does not align with circular-economy principals, as the value of the plastic material is lost, although it ensures that **less plastic enters the nature environment and water systems.**

Although LCA results indicate that closed-loop recycling (i.e. production on high quality HDPE/PP/LDPE and food-grade rPET recyclate) is the environmentally preferable option, these results are not judged to be robust within the data limitations of the study. The high technology and closed-loop recycling options have higher recycling processing impacts than low-technology recycling, as practiced by SMEs in Cambodia, due to increased energy, material and water inputs for processing. However, the higher technology systems produce better quality recyclate and therefore offset an increased amount of virgin plastic production, resulting in greater avoided impacts. The differential between these two (i.e. the net impacts) depends on recycling energy inputs, recycling yields and the quality of output recyclate (see Section 4.3) and therefore results are not definitive on which option is preferable.

In order to improve the life cycle environmental sustainability of recycling operations, it is key to **improve the quality (especially cleanliness) of incoming plastic waste, minimise energy consumption and reduce chemical consumption**. Improved plastic waste quality has numerous knock-on impacts, including reducing the water and chemicals required for cleaning, reducing the amount of waste generated from processing and improving the quality of output recyclate. If energy consumption cannot be reduced, it is also possible to mitigate impacts by switching to cleaner energy sources (e.g. natural gas over diesel) or preferably renewable energy sources.

[33] Water scarcity is an individual impact category within the human health and ecosystem quality "single-score". It is therefore included in the aggregated "single-score" results presented and analyzed.

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