# Applications of Recycled Plastics
# and
# Life Cycle Assessment

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# Abstract

Polymers, a unique invention of last century, have influenced the everyday aspects of human life. However, its widespread usage and applications, the non-biodegradable characteristics of polymer materials, and waste mismanagement have caused permanent negative damage to the environment. Plastic debris is found everywhere – including forests, river streams, lakes, coastal lines, ocean surfaces and even the seabed. It is affecting humans and is reported as a cause of death to wildlife, birds and sea animals. When plastic waste was understood and managed well, plastic wastes could be utilised as a high value material. However, plastic waste management and recycling operations are not simple processes owing to their multitude of complexities directly or indirectly determining the environment and economic sustainability of an end-of-Life (EOL) operation.

Life cycle assessment (LCA), a cradle-to-grave technique, is a holistic methodology to evaluate and assess the environmental impact of a product or a process. This research is based on conducting LCAs on various applications of recycled plastics to estimate their environmental impacts. LCA was conducted on composites containing recycled plastics to estimate environmental impacts when utilised in the construction and automotive markets in replacing virgin composites or traditional materials like wooden products. Composites based on recycled plastics were found to produce significant environmental benefits in the construction industry. Automotive applications, in a best-case scenario, were found to have an environmental profile similar to virgin material. However, combinations of construction and automotive applications are one of potential opportunities to increase the consumption rate of recycled plastics. The choice of LCIA methods was found to have a significant effect on the LCA outcome. Various contributions leading to different outcomes are evaluated and addressed.

**Declaration:**

Most of the LCA work was conducted around 2010 to 2014. LCA methodology, impact assessment methods, inventory, characterisation values, standards, impact factors and policy may have changed in the intervening period.

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# List of Abbreviations

| | |
|---|---|
| ADP | Abiotic resource depletion potential |
| CED | Cumulative energy demand |
| CF | Carbon fibre |
| CML | Institute of Environmental Sciences of the University of Leiden |
| DMT | Dimethyl terephthalate |
| EDIP | Environmental Development of Industrial Products, Denmark |
| EG | Ethylene glycol |
| EI/EI99 | Eco-indicator 99 |
| EOL | End of Life |
| ER | Energy recovery |
| FF | Flax Fibre |
| FRV | Fuel reduction value |
| FU | Functional unit |
| GF | Glass Fibre |
| GWP | Global warming potential |
| H-S | Halpin Tsai |
| HIPS | High impact polystyrene |
| HDPE | High density polyethylene |
| LCA | Life cycle assessment |
| LCI | Life cycle inventory |
| LCIA | Life cycle impact assessment |
| LCP | Liquid crystalline polymer |
| LDPE | Low density polyethylene |
| LLDPE | Linear Low-density polyethylene |
| LTR | Life time ratio |
| MPW | Mixed plastic wastes |
| MR | Mechanical Recycling |
| NEDC | New European Driving Cycle |
| NIR | Near infrared |
| NF | Nano fibre |
| OLD | Ozone layer depletion |
| PCTFE | Polychlorotrifluoroethylene |
| PE | Polyethylene |
| PEEK | Poly ether ether ketone |
| PEKK | Polyether ketone ketone |
| PMMA | Polymethyl methacrylate |
| POCF | Photochemical Oxidants Formation |
| PI | Polyimide |
| PIB | Polyiso-butylene |
| PP | Polypropylene |
| PVC | Polyvinyl chloride |
| RHDPE | Recycled HDPE |
| ROM | Rule of mixtures |
| RPS | Recycled Polystyrene |

| | |
|---|---|
| RPP | Recycled polypropylene |
| SLCA | Streamlined LCA |
| TRADA | The Timber Trade Federation |
| $V_f$ | fibre volume fraction |
| VPP | Virgin polypropylene |
| VOC | Volatile organic compounds |
| WO | Without |
| Wt% | Weight % |

# Glossary of Terms

1. ***Bio fibre****:* Fibrous reinforcement made from bio-based raw material.
2. ***Closed-loop recycling****:* Is the process by which waste or used component is collected, recycled to make something new component in a same application. Example: PET water bottle is recycled to new PET water bottle.
3. ***Environmental credits:*** This indicates decrease of environmental emissions normally represented as a negative value in LCA.
4. ***Environmental impact:*** The effect that the activities of people and businesses have on the environment.
5. ***Open-loop recycling:*** Open-loop recycling is any recycling process where the waste materials are converted into a new product in a different application. Example: PET water bottle is recycled to a fleece.
6. ***Plastic lumber:*** is a plastic form of lumber (wood like appearance) made of virgin polymer contains mostly of polymer and may contain some additives.
7. ***Polymerisation:*** Is a chemical process of monomer molecules reacting together to form a polymer chain.
8. ***Recycled plastic lumber:*** is a plastic form of lumber (wood like appearance) made of recycled polymer (made of one or multiple materials) contains mostly of polymer and may contain some additives. Recycled HDPE lumbers, comingled recycled plastic lumber fall into this family
9. ***Reinforced plastic lumber:*** Lumber made of plastics and reinforcement additives such as glass fibre, mica, etc.
10. ***Reinforced recycled plastic lumber:*** Lumber made of recycled plastics and reinforcement additives such as glass fibre, mica, etc.
11. ***RPP-GF:*** Recycled polypropylene reinforced with virgin flax fibre
12. ***RPP-GF:*** Recycled polypropylene reinforced with virgin glass fibre
13. ***Upcycling:*** Open-loop recycling technique to manufacture a product of higher value than the original application. Example: PET water bottle is recycled to a foam sheet for marine application.
14. ***VPP-FF:*** Virgin polypropylene reinforced with virgin flax fibre
15. ***VPP-GF:*** Virgin polypropylene reinforced with virgin glass fibre

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# Chapter 1: Introduction

Polymer Materials are one of the marvellous inventions of the modern age. They play a very crucial role in our life and their applications are numerous, as shown below in Table 1.1. The benefits of these polymeric materials are many, and it has driven demand from 1.7 MT in 1950 to 311 MT in 2014 (1) as plastics have become deeply embedded in the market and everyday life. A world without polymeric materials would be very challenging and, in some cases, plastic materials are non-substitutable. Polymer alternatives could be very energy intensive, affect food & medical hygiene, and it could be unsafe and/or unsustainable to replace polymers in some of the applications. A recent study by Dell & Trucost (2) indicates that replacing polymers with alternative materials would increase damage to human health & ecosystem, carbon emissions and marine pollution significantly.

In 2018, the International Energy Agency reported that plastics are expected to occupy the major share in oil demand in 2050 as fuel demand is expected to decrease due to energy efficient transportation systems, biofuels, alternative energy sources and electrification (2)(3). Owing to environmental concerns, some of the non-critical applications could get replaced by biodegradable polymers, non-polymeric materials and biomaterials. Even then the volume demand for plastic materials and the generation of plastic waste will be huge. The simple and straightforward solution is to recycle polymeric materials and create a circular economy by carefully designing or redesigning the whole lifecycle of the product.

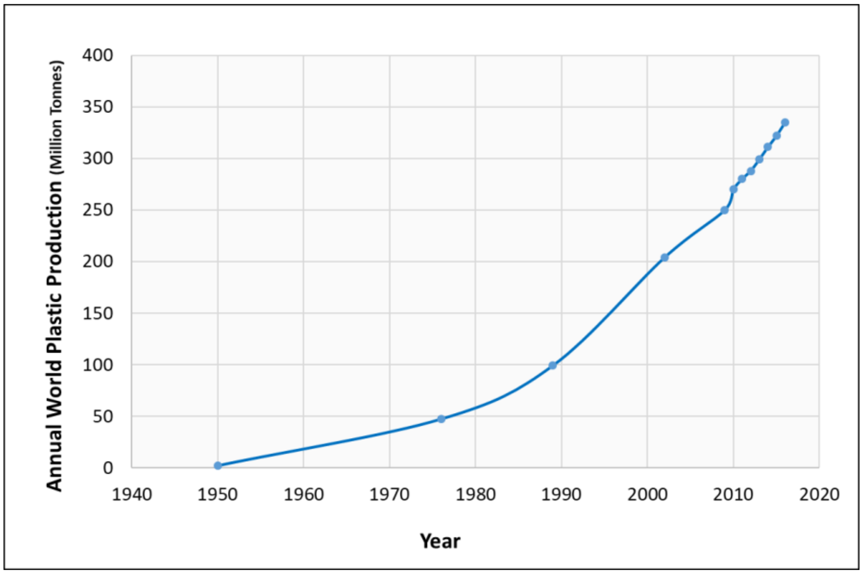


**Figure 1. 1 World plastic production from 1950 to 2016 showing signifcant growth of plastics** (1)

| Category | Typical Examples | Common Polymer Materials Used |
|---|---|---|
| Flexible Packaging | Polymer (single & Multi use) Bags & Films | LDPE, LLDPE |
| Semi-Rigid Packaging | Thermoformed Packaging such as medical packagings | PCTFE, PVC, PP |
| Rigid Packaging | Milk Bottles and Water bottles | HDPE, PP, PET |
| Medical Applications | Blood Bags, Syringes, Inhalers and Catheters | PVC, PU, PP, PSU, POM |
| Body Implants | Artificial Bones, Cranial implants (artificial Skull), Prosthetic Legs | PEKK, PEEK, UHMWPE |
| Electrical & Electronics | Laptops, LED/LCD Screens, Washing Machine and Refrigerators | HIPS, PP, PS, PA,ABS/PC, SAN, PU |
| Agriculture | Green house films, tunnels, shading | LDPE, EVA, PVC, PMMA |
| Automotive | Body Panels, Air Bags, Tyres, Battery Covers and Bumpers | ABS, HIPS, PA, PP, ABS, PC |
| Aerospace | Wing Spars, hydraulic tubings, aircraft interiors and wind screen | Epoxy-CF, PEEK-CF, PTFE, PPSU, PEI |
| Oil & Gas | Valve components, Seals, Bearings, Compressor Rings and Packings | PTFE, PEEK, PI, PPS |
| Civil & Infrastructural | Foam Insulation Panels, Window Frames and Plumbing Components | PVC, PU, PS, PP |

**Table 1. 1: General applications of plastics and polymeric Products (4)(5)**

As we can see from Figure 1.1, the manufacture of polymeric materials has grown significantly since the second world war. This has resulted in huge amounts of plastic waste which could be because of reasons such as over exploitation of single use plastic products due to low economic value, lack of equivalent sustainable alternatives, product design, non-degradability, waste collection infrastructure & and waste management (4). This huge accumulation of plastics is not only from packaging applications even though packaging's are the major contributor. Overall plastics wastes in UK is estimated to be around 3.7 million tonnes (2014 Statistics) out of which the packaging sector contributes around 60% (5). The remaining 40% is predominantly from WEEE, Construction & Demolition, End of Life of Vehicles and Agriculture (6). As emphasised by universities, local authorities and governments, recycling and circular economy are the potential and promising solution to handling plastic waste. In this plastics waste management & circular economy, lifecycle assessment plays a major & critical role in evaluating waste management options, product design, manufacturing & recycling techniques etc.

Good waste management systems and practices will significantly help society in manufacturing sustainable products, recovering energy and fuel from waste and much more. Apart from these industrial benefits, it will also help to reduce the amount of plastic waste ending up in our eco-systems, river streams, oceans, seabeds, etc. It was estimated in 2010 that 4.8 - 12.7 million tonnes of plastic waste ended up in the ocean (7). Plastic waste ending up in the eco-system and marine environment is of serious concern to our entire society. The volume of consumption, along with lightweight and non-biodegradation nature of polymers, worsens the situation and forms the underlying cause for plastic waste accumulation in sea beds, coastal lines, fresh water, woodlands and arctic regions (8,9), including irreversible damage to marine habitats (10).

Plastic waste in a marine environment has consequences, such as: entanglement, ingestion, organisms damage, suffocation and species transport (11). Entanglement of marine habitats with plastic fragments are reported to cause mortality of marine organisms and affect their ability to find food, defend against predators and reduces their overall fitness (12). Mortality due to ingestion of smaller plastic flakes or particles (less than 5mm) was reported to have a direct correlation in smaller sea birds (13) as ingestion results in the obstruction of gastrointestinal tracts. Ingestion was also reported in more than 260 other species including mammals and fish (10). As plastics contain toxic additives, the ingestion of microplastics increases toxic exposure to ocean species (14).

The fate of these plastic waste materials ending up across the eco-system are primarily due to waste management practices, poor infrastructure, mismanagement, littering, the volume of single-use products, intrinsic polymer properties and lack of awareness of the value of recycled products (7), and are likely to cause long-term irreversible damage to environments and ecosystems which need clear assessment of the environmental impact, tracing back to its root cause of the source for problem identification and resolution.

As shown in Figure 1.2, Geyer et al. (15) estimated that a total of 8300 million metric tonnes of produced virgin plastics between 1950 to 2015 resulted in the generation of around 6300 million metric tonnes of plastic waste, out of which only 9% of plastic waste was recycled and 12% incinerated, resulting in 79% of plastics ending up either in landfill or in the natural environment. A current recycling rate of 9% puts enormous pressure on all aspects of the whole plastic waste management system to reduce or mitigate the environmental threats posed by plastic waste to our society and eco-system.

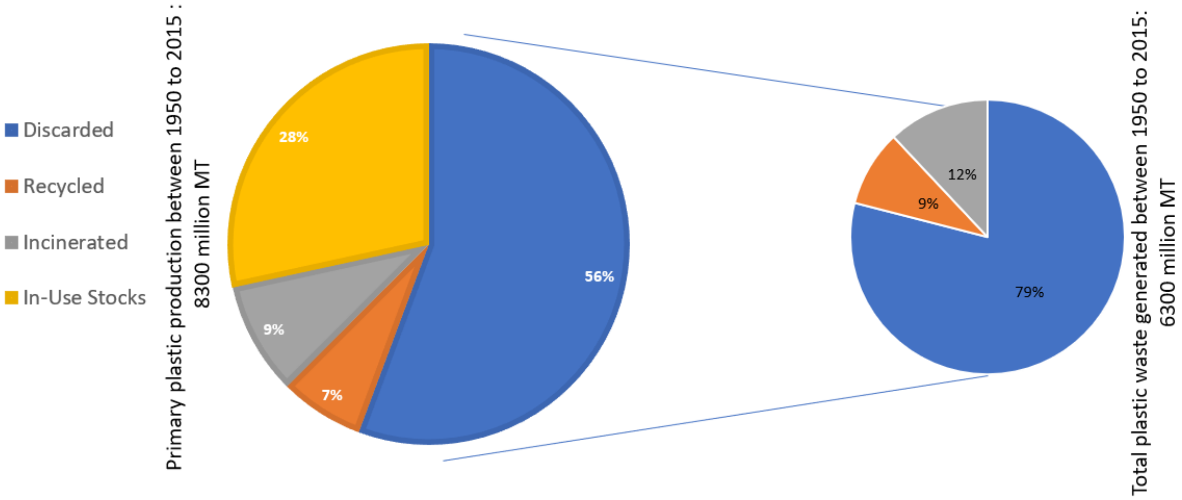


**Figure 1. 2: Global production and fate of plastics produced between 1950 to 2012 covering recycling and incineration** (15)

## 1.2 Life Cycle Assessment

Life cycle assessment is a cradle-to-grave technique in which a product is evaluated for its environmental impact considering all stages of its life i.e. from cradle to grave. In this cradle-to-grave analysis, the impacts are included from the extraction of raw materials; the processing, manufacturing, and fabrication of the product; the transportation or distribution of the product to the consumer; the use of the product by the consumer; and the disposal or recovery of the product after its useful life. The life of a product from cradle to grave is shown schematically in Figure 1.3 for better understanding.

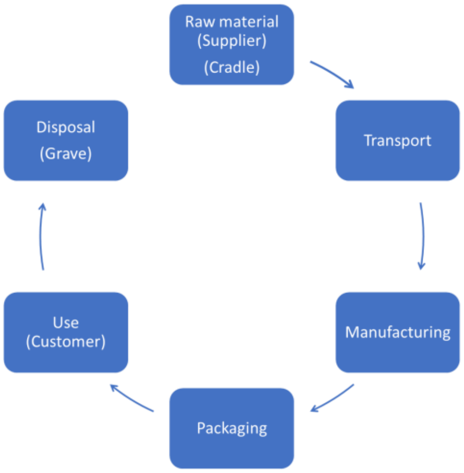


**Figure 1. 3: Life cycle of product depicting the cradle-grave stage (16)**

If a product or a process is to be selected which

- Should not damage or deplete the Earth's natural resources and fossil fuels
- Must demonstrate less or no damage to human, plant and animal health
- Generates less or no waste and pollution
- Should decrease or eliminate the environmental problems rather than move the impact from one stage to another

then Life Cycle Assessment is the best tool of choice.

ISO 14040 defines Life Cycle Assessment (LCA) as "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system" and Life Cycle as "Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal" (17).

These life cycle assessments are part of the environmental management standards ISO 14040:2006 and 14044:2006. The main outcomes of conducting LCA on a product or a process are:

- Waste minimization
- Selecting a less polluting product or a process in all stages
- To select less expensive products (this helps in marketing).

Apart from marketing, the life cycle assessment will generate positive impacts on human health, ecosystems and natural resources. The main goals and objectives of LCA are shown in Figure 1.4.

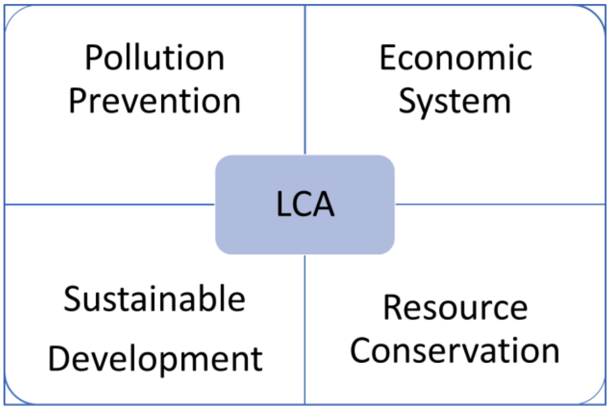


**Figure 1. 4: Goals and objectives of Life Cycle Assessment (18)**

As shown below, there are other techniques available to evaluate and reduce environmental impacts. However, LCA is the only technique which will cover the whole life cycle of the product from cradle to grave, evaluating all of the potential environmental impacts along with visibility to optimise and reduce whole life cycle environmental impacts.

- Environmental Risk Assessment (ERA) (19)
- Water Footprint Analysis (20)
- Carbon Footprint (21)
- Cumulative Energy Demand (CED)(22)

## 1.2.1 Limitations of LCA

- Uncertainties: Since LCA involves extensive data collection and analysis, the uncertainty of inventory parameters, assumptions of allocations & cut-off, and environmental models are possible in LCA (23).
- Comparability: A study published by Liu et al.(24) compared the global warming potential (GWP) of laptops ranging from 12” to 17” screen size. Results indicate a GWP range between 50-450 kg $CO_2$ Eq. Narrowing down the comparison range between 12.1” to 14.1” indicates a GWP range between 50 to 250 kg $CO_2$ equivalent, indicating a 500% difference between laptops which do not vary by more than 2” screen size. Owing to various methodologies, assumptions and system boundaries, comparative LCA is a challenge and a limitation.
- Life cycle inventory (LCI) data (25): This is one of the major limitations and challenges in LCA. This is particularly challenging in manufacturing industries where products manufactured will have different impacts based on the location of suppliers, manufacturing volume (for instance: single cavity and multicavity injection molding), cycle time, process wastes and % rejects. However, when LCI is not available, analysts have to estimate the data from available resources and publications which will lead to assumptions and estimation which could lead to data inaccuracy.

## 1.3 Research Motivation

Life Cycle Assessment studies on plastics recycling have been reported by several researchers and some of them are cited (26–41). In this research, LCA studies will be demonstrated from a Materials Engineering and Product Development perspective. Objectives of this research are as follows:

- To evaluate products manufactured from recycling on different end-use applications
- To evaluate the environmental impact of recycled plastics replacing existing structural or semi-structural products
- To compare various LCIA methods and report 'how & why' difference is occurring.

## 1.4 Thesis Structure

The structure of the thesis will be as follows:

***Chapter 1: Introduction***

Covers introduction to Plastic Wastes, Plastics Recycling, LCA and Research Motivation. This chapter also covers a brief introduction to LCA methodology.

***Chapter 2: Literature Review***

A brief review of plastics recycling studies which are relevant to this research will be included. This chapter also includes relevant details required from various end-of-life scenarios such as feedstock recycling, incineration, emission guidelines, and mechanical recycling. Studies on reinforced recycled plastics such as the effect of various fillers and fibres on properties are reviewed. Various life cycle assessment studies on polymer recycling and waste management relevant to this research are included.

***Chapter 3: Reinforced Recycled Plastics and their Applications***

This chapter demonstrates the LCA of recycled polymers in various applications – particularly focusing on Civil, Infrastructural and Automotive applications. Composites based on recycled matrix with glass and flax fibre will be analysed from a life cycle perspective in various applications. This chapter will also cover the estimation of environmental impacts of various recycled products and its applications through CML and Eco-indicator-99 methods analysing individual impacts and the overall single score in both Civil and Infrastructural and Automotive applications.

***Chapter 4: Estimation and Comparison of Environmental Impacts of Recycled Plastic Lumber with Softwood Lumber***

This chapter analyses the environmental impacts of recycled plastic lumber against softwood lumber. Softwood lumber finds several semi-structural applications in construction industry. Life cycle inventory of both softwood lumber and recycled plastic lumber was built from peer-reviewed literature and ecoinvent inventories. The impacts of various life cycle stages will be evaluated though CML and Eco-indicator 99 methods and impacts were compared in CML and Eco-indicator methodology in various lifetime ratios.

***Chapter 5: Plastics Recycling and Life Cycle Impact Assessment***

There are various impact assessment methods available in LCA methodology. Plastics recycling will be analysed through LCIA methods such as CML, EDIP, CED and Eco-indicator methods. LCIA results will be compared and investigated to identify the reasons behind any differences.

***Chapter 6: Conclusion and Future Work***

***Chapter 7: References***

## 1.5 Life Cycle Assessment-Methodology Overview

Life cycle assessment is a cradle-to-grave approach for assessing a material, product or a technology. This starts with the acquisition of raw material from the Earth (cradle) and ends when the final product is disposed of (grave). This methodology helps us in all stages of a product such as designing, manufacturing, service, recovery and disposal, with the aim of minimising the resource use and environmental impact.

This methodology consists of following stages (17,42,43):

- Goal and Scope definition
- Life Cycle Inventory Stage (LCI)
- Life Cycle Impact assessment (LCIA)
- Life Cycle Interpretation

ISO 14040 (17) depicted these phases as framework of LCA as shown in Figure 1.5.

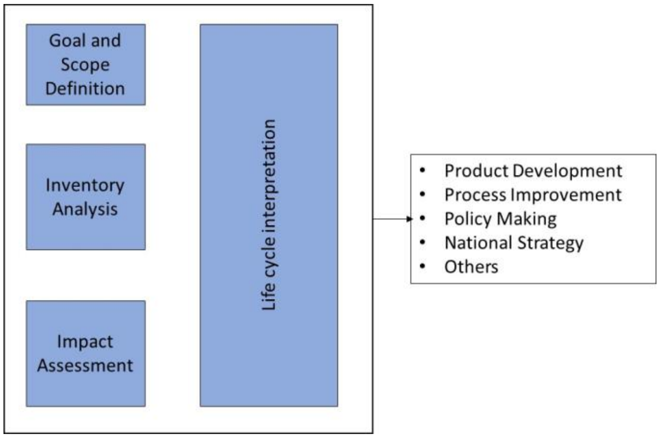


**Figure 1. 5: Life Cycle Assessment Framework: Stages of LCA (17)**

## 1.5.1 Goal and Scope Definition

### 1.5.1.1 Defining the Goal

This stage of life cycle assessment defines the method of conducting LCA. This phase helps us to identify the following information:

- The type of information needed to conduct LCA
- The level of accuracy required to get a meaningful result
- The method of interpretation of results
- Assumptions and guidelines
- The type and format of report required

In life cycle modelling, the actual process, product or technology is mathematically simulated to calculate the environmental impacts. But, due to the lack of data availability, time and financial constraints, the simplification of the actual process is done, that is deviation from reality, to model a product. But these deviations sometimes distort and might give misleading results. In order to avoid this, careful definitions of goal and scope are needed.

### 1.5.1.2 Defining the Scope

Identification of functions to be analysed and interpreted in terms of physical quantity.

Definition of Functional Unit (FU): This is a key element of LCA and hence needs unambiguous and clear definition. This functional unit is a measure of function of the system, and it provides a reference to which inputs and outputs can be related. If the intended study is for the comparison of two products, then the comparison of its functional unit gives the actual impact of one product over the other.

LCA is structured and studied around functional unit which defines fundamental basis of a particular LCA study. All analysis such as inputs, outputs, emissions, individual unit processes, impact assessment & interpretation are calculated with respect to functional unit. FU remains common & same for all products of interest and ensures calculations are normalised with respect to the FU. FU is recommended to be defined based on quantified functions rather than mere products (17,44).

Example: Comparison of different types of black pen

- *Capable to draw 0.5mm thick & 10km long black line and shelf life of 5 years rather than pen made of ABC manufacturer with XYZ manufacturer.*

System Boundaries: A product will have interlinked multiple unit processes and system boundary determines which unit process is required to be added inside the functional unit. A product can be interrelated to another product in a complex way. The tracing of all input and output flows are not possible and excluding certain processes/products out of the functional unit might distort the entire results. Hence, the careful definition of system boundaries determines the entire result of LCA. Example: Typical unit processes, inflows and outflows included in the system boundary are:

- Acquisition of raw materials
- Transport involved within unit processes and between unit process
- Quantified use of electricity, fuels and heat
- All kinds of Inputs and outputs in individual unit processes in manufacturing stage
- Inputs and outputs associate in use-phase
- Inputs and outputs associate after its useful phase: Disposal

### 1.5.2 Life Cycle Inventory (18)(17)

This is the data collection phase – the most demanding and time-consuming step in LCA. Some databases are available which comprise commonly used processes and products. Some of them are:

- Buwal 250 (45): Age 1996-2000 (46)
- Ecoinvent (47): Age 1990-2010 (48)

- U.S. Life Cycle Inventory Database (49): Age 1990-2006 (50)
- European Reference Life Cycle Database (ELCD) (51): Age 2006-2010 (52)
- Plastics Europe : Age 1993-2010 (53)

This LCI phase involves the creating of flow diagrams – specifying the unit process and collection of data. As shown in Figure 1.6, the main outcome of this LCI is the quantification of flow of all inputs from the environment, across the boundary, into the system, and the flow of all outputs from the system, across the boundary, to the environment. This LCI helps us to compile the environmentally significant input and output of a product system. The activities involved in the life cycle inventory stage are:

1. Construction of a flow chart according to system boundaries defined in the goal and scope definition stage.
2. Data collection for all unit process in the functional unit.
3. Calculation of environmental load of the entire system.

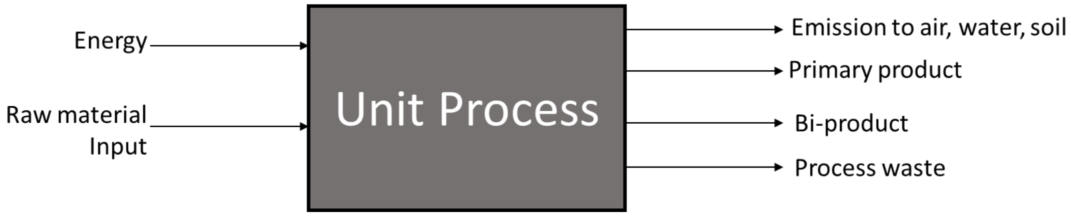


**Figure 1. 6: Schematic representation of life cycle inventory** (42) ***showing inputs and outputs of a unit process***

### 1.5.3 Life Cycle Impact Assessment

In the life cycle inventory stage, the environmental loads are quantified. In this impact assessment stage, those environmental loads are converted into environmental impacts. This is a translational stage.
The reasons for this translational process are:

- To understand the environmental effects of inventory data
- The life cycle inventory data consists of so hundreds of parameters. In this phase, those parameters are grouped. This leads to a reduction in the number of parameters; hence, this helps to reduce mathematical complexity as well as improve comparability.

### 1.5.4 Phases of Life Cycle Impact Assessment

The different phases available in impact assessment are shown in Figure 1.7. Impact categories relevant to the LCA study are identified to cover all inventory data and assigned to impact categories. In characterisation steps, all inventory data is converted to a quantified impact category. This is carried out using science-based conversion factors called Characterisation factor or Equivalency factor (42). Characterisation factor examples for some of the emissions contributing to global warming potential are shown in Table 1.2. The Characterisation step can be represented as:

*Inventory Data X Characterization factor = Impact Indicators*

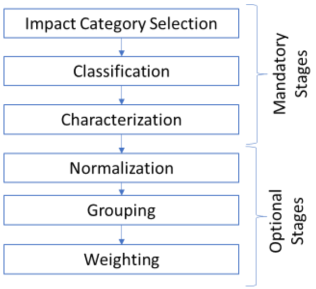


**Figure 1. 7: Phases of life cycle Impact assessment (17)**

The impact indicators close to the inventory results are having lower levels of uncertainty, and indicators far away from inventory are having high levels of uncertainty. The different indicators with midpoint and endpoint are shown here in Figure 1.8.

| | | **100-year time horizon** |
|---|---|---|
| **Emmission** | **Chemical Formula** | **Characterisation Factors for calculating** |
| CarbonDioxide | $CO_2$ | 1 |
| Methane | CH4 | 28 |
| Nitrous oxide | $N_2O$ | 265 |
| CFC-11 | $CCl_3F$ | 4,660 |
| Methyl bromide | $CH_3Br$ | 2 |

**Table 1. 2: Characterization factors for global warming potential calculation** (54)

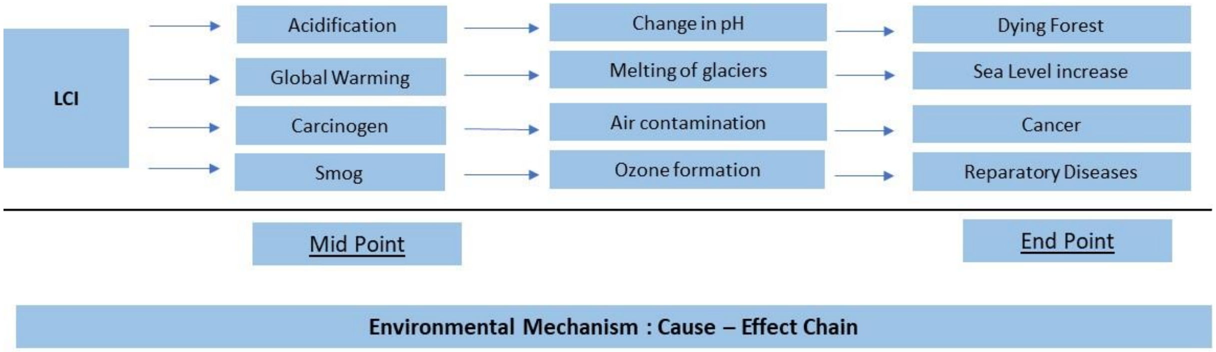


**Figure 1. 8: Impact Category Indicator: Midpoint and Endpoint – based on reference** (43)

Normalisation is a critical step which makes impact indicator data comparable with each other. This is done by dividing indicator results by a reference value. The reference value can be: total emissions or resource use for a given area, region or a country; or a ratio of one alternative to another; or the highest value among all options (height-based normalisation). Height normalisation method used in this thesis is a technique, which is practiced in chemical laboratories, indicates that highest value is represented as 100% and other values are represented on pro-rata basis with respect to maximum value. This technique is mainly useful when multiple values of various units are presented in various units. In grouping, one or more indicators are grouped together. This helps in the analysis and presentation of results. Some of the common grouping methods are grouping according to type of emission (air, water land) or according to priority (High risk, Low risk, Medium risk). In weighting step, the relative importance of each environmental impact is weighted against all others. The weighting factors are based on risks or level of damages. Weighting step helps achieve 'Environmental single score' which makes comparability considerably easier and supports decision-making (55). Impact assessment methods (Eco-indicator 99, EDIP, EPS) offer weighting step in the method, and they follow different approaches (56) in weighting, such as:

### Panel Weighting

This method involves groups of people – seeking their opinion on what is important. The downside of this approach is different people in the panel will have different environmental knowledge and experiences influencing the weighting scores. Eco-indicator 99 was applied in this approach where questionnaires were sent to 365 participants with questions covering three major damage categories: damage to human health, damage to eco-system quality, and damage to resources (55,57).

### Monetisation

This method is based on the cost of repairing or preventing a damage – allowing a summary of the damages based on their relative damages. The complexity is knowing how to value the maximum acceptable damages and how to value two different impacts. For instance: how much value is acceptable for damage to human health? Values are obtained from individuals as 'Willingness to Pay'(WTP) to avoid or prevent environmental damage with the present state of the environment as the target (58).

Distance to scientific target

This is based on scientific targets and how far away each impact category is. Impact category values closer to targets get lower weighting, and vice-versa if impacts are away from target. The challenges in this approach are the non-availability of scientific targets in some of the categories, and ever-changing target values in some of the categories.

Distance to policy target

National or international policy or reduction targets are used as a benchmark target. For instance, the UK government is aiming to achieve an 80% reduction in global warming gases by 2050 (59). The issue in this approach is that policy targets are political targets and may not resemble real environmental seriousness. EDIP 2003 weighting method is based on political targets.

Weighting step in LCA is a well-debated subject owing to its subjectivity (60). ISO14042 restricted weighting step for all LCA studies disclosed to the general public. Concerns were also raised on the aggregation step used to obtain weighted single scores – particularly on compatibilities and dependencies between individual impact categories and linear relationship used in obtaining weighted results (61).

### 1.5.5 Impact Categories

Some of the selected impact categories are briefly explained below:

#### Global Warming

Radiant energy, also known as short-wave radiation, received from the sun is reflected or re-emitted from the atmosphere or from Earth's surface as longer-wave infrared radiation (IR). Some of the emitted radiation is absorbed by gases, aerosols, water vapour and particles in Earth's atmosphere and results in increasing the Earth's atmospheric temperature causing a 'natural greenhouse effect'. Some of the gases ($CO_2$, $CH_4$, $N_2O$) released to the natural atmosphere owing to man-made activities also contribute to the greenhouse effect (62), causing increased global warming. The consequences of global warming are increase in sea level and fluctuations in climatic conditions & rainfall which leads to spread diseases and impacting eco-system (63).

## Resource Depletion

This impact category includes extraction of different types of materials including both living and non-living resources from the environment. Resource depletion could be sub-categorised into following types:

- Abiotic resources cover materials such as minerals, crude oil and iron ore which are regarded as non-living (64).
- Biotic resources cover materials such as rain forests, biomass and elephants which are regarded as living (64).
- Flow resources cover sources like solar energy, wind, surface water and ground water (65).

There are various methods through which resource depletion could be measured and one of the well-known methods, CML method, quantifies depletion potential through quantity of resources used, rate of depletion against reserves and rate of depletion of reference substance (64).

## Acidification

Industrial process emissions containing oxides (such as NOx and $SO_2$) contribute greatly towards acidification impact. These oxides in contact with water / moisture will convert to Nitric acid ($HNO_3$) and Sulphuric acid ($H_2SO_4$) respectively (65). Acidification impacts is reported to cause damages such as fish morality, affecting health of forest species, acid attack on metallic structures, monuments and buildings (65). Proton release capability ($H^+$ ions) of these acidifying pollutants are used to measure the acidification potential (42).

## Ozone Layer Depletion

Ozone ($O_3$), natural component of Earth's atmosphere (stratosphere), forms a band around entire globe is referred to as 'Ozone Layer'. Ozone layer helps to filter out harmful ultraviolet layer radiation from the sun. Destruction or thinning of this ozone layer is referred to as 'Ozone Layer Depletion (OLD)' (63). Reduced ozone quantity in the atmosphere would lead to more exposure of UV radiation on earth surface. This exposure is expected to cause damages to human health (such as skin cancer and cataracts) and natural environment (such plant growth, nutrient distribution and plant diseases) (66). Some of the common ozone depleting substances are halocarbons such as chlorofluorocarbons (CFCs), tetrachloromethane and methyl bromide (65). OLD of a substance is measured based on damage caused by quantity of OLD substances emitted in relation to damage caused by emission of CFC-11 (64).

## Photochemical Oxidants Formation

Photochemical Oxidants Formation (POCF) impact category mainly refers to the formation of oxidizing substances such as Ozone and Peroxy acytal nitrate (PAN). POCF compounds are formed when volatile organic compounds (VOCs) react with nitrogen oxides and other oxygen compounds in the presence of sunlight. Nitrogen oxides (NOx) and other oxygen compounds are naturally present in Earth's atmosphere (62). Photochemical oxidants expected to cause photochemical smog (Los Angeles smog) which are well reported to cause respiratory illnesses and damage to crops (42). POCF is measured based on quantity of VOC emitted and it potential to form ozone against ethylene as a reference substance.

## Eutrophication

Eutrophication is related to impacts associated with over-supply of nutrient than its natural rates in both soil and water bodies (42). Materials that generally fall under this category are Nitrogen(N) and Phosphorus compounds(P). This excess supply of nutrients are reported to cause shift in species composition in terrestrial or agricultural eco-system and increased biomass production in aquatic bodies (64). Shift in species composition indicates that increased growth of particular type of spices rather species which are characteristic to a particular area or a stream (67). Increased biomass production in aquatic environment leads to oxygen depletion in water bodies causing difficulties for survival of aquatic life (62). Eutrophication is measured based on quantity of emissions and their potential to biomass production against its reference substance ($PO_4^{3-}$) (64).

## Toxicity

Toxicity is a complex impact category as it covers materials (such as chemicals, heavy metal, solvents) causing various toxic activities ( human toxicity, marine eco-toxicity and terrestrial eco-toxicity) in various different modes (such as carcinogenicity, neurological suppression and genetic damage) (42). Impact assessment method generally sub-categorises toxicity to Human and Eco-Toxicity and further minor categories so as to group and simplify the inventory results. Toxicity potential is quantified through complex calculation process and method unitized in CML method contains four factors (64) as shown below:

- Fate factor – covers residence time and degradation mechanism.
- Transfer factor – covers quantity of substance transferred from source or substrate to carrier
- Exposure factor – covers exposure of chemical through routes such as respiration, drinking or food intake
- Effect factor – Covers hazard characteristic & toxicity amplitude of a particular chemical.

More details on impact assessment methodology could be obtained from Chapter 5 Section 5.3 and following references (42,64,68).

### 1.5.6 Readymade LCIA methods

There are a number of ‘readymade LCIA methods’ currently available. The main advantage is that the LCA analyst does not need to go in-depth into the procedure of the different impact assessment methods. The procedure is programmed to do all mathematical calculations. Some of the readymade methods are:

1. Eco-Indicator 99 (68)
2. RECIPE (69)
3. EPS (70)
4. CML (64)
5. IPCC (71)

Each method differs on geographical boundaries, single scores, normalisation, reference values and weighting.

### 1.5.7 Life Cycle Interpretation

The objectives of Life Cycle Interpretation are to analyse results, reach conclusions, and explain limitations, based on the results from inventory and impact assessment data. This step gives understandable, complete, consistent results of an LCA study in accordance with the goal and scope of the study.

Key steps in interpreting the results of LCA:

- Identification of significant issues based on LCI and LCIA
- Ensuring completeness, sensitivity and consistency checks - Evaluation Step
- Conclusions, recommendations and reporting

Further details on LCA methodology can be obtained from references (18,64,72–74)

### 1.5.8 Streamlined LCA

Conducting a full scale LCA could be challenging considering time limitations, resources and data availability. Considering this challenge, some studies have been performed as streamlined LCA which is a simplified version of full scale LCA (75–77). Streamlined LCA is a technique which is rigorous enough to act as guide for industries covering key environmental aspects, but simple enough to perform. Streamlining of LCA could be conducted through following approaches (78):

- Excluding or limiting process which are of minor importance
- Excluding or limiting a life cycle stages
- Including only selected impact categories
- Applying cut off rules
- Using data based on qualitative analysis
- Use proxy or substitute data

LCA studies in this thesis is based on streamlined approach as whole research is intended to support industrial product development activity. However, LCA studies conducted in research are detailed enough to act as guide as well as to maintain credibility.

# Chapter 2: Literature Review

This chapter is presented in several sections covering the literatures on the end-of-life of polymers, such as, mechanical recycling, incineration, pyrolysis and landfill, focusing on technology and their benefits and limitations. The last part of this chapter covers literature on LCA studies on various types of plastic waste recycling scenarios.

## 2.1 Management methods for plastic waste

A material of a million uses, polymers, meet the specifications of thousands of applications from footwear to aerospace engines. A large application portfolio, along with an affordable price, has driven a massive consumption of plastics resulting in an accumulation of a huge amount of plastic waste. As shown in Figure 2.1, plastic production was around 1 billion tonnes in 1980 and it has increased to around 8 billion in 2015, with a rate of increase of around 200 million tonnes per year. This rate of production resulted in the generation of 6,300 million metric tonnes of plastic waste out of which 12% is incinerated, 9% is recycled and the remainder is discarded in landfill or the natural environment. As shown in Figure 2.1, mechanical recycling and incineration were initiated only in the 1980s covering less than 1% of plastic waste with a gradual rise to 20% in 2015. This slow rate of recycling and incineration resulted in the accumulation of around 4,900 million tonnes of plastic waste in our natural environment (15).

The reasons for this low recycling rate are: waste mismanagement, poor waste collection infrastructure, littering, product design & applications, complex product types, chemistry, various material categories and public awareness. Among these, multiple materials, chemistry, product design and applications challenge the waste management system to follow a single end-of-life (EOL) technique for all plastic wastes. This resulted in various EOL scenarios of plastic waste, as shown in Figure 2.2. Mechanical recycling or Thermo-mechanical recycling is generally preferred as it is reported to save around 60 GJ/t when it replaces virgin plastics in a 1:1 ratio (79). When there is a limitation for mechanical recycling, other secondary recycling methods such as chemical recycling, incineration, and pyrolysis were preferred (80). Secondary recycling techniques such as feedstock recycling, chemical recycling, incineration energy recovery and pyrolysis give various options of managing plastic waste.

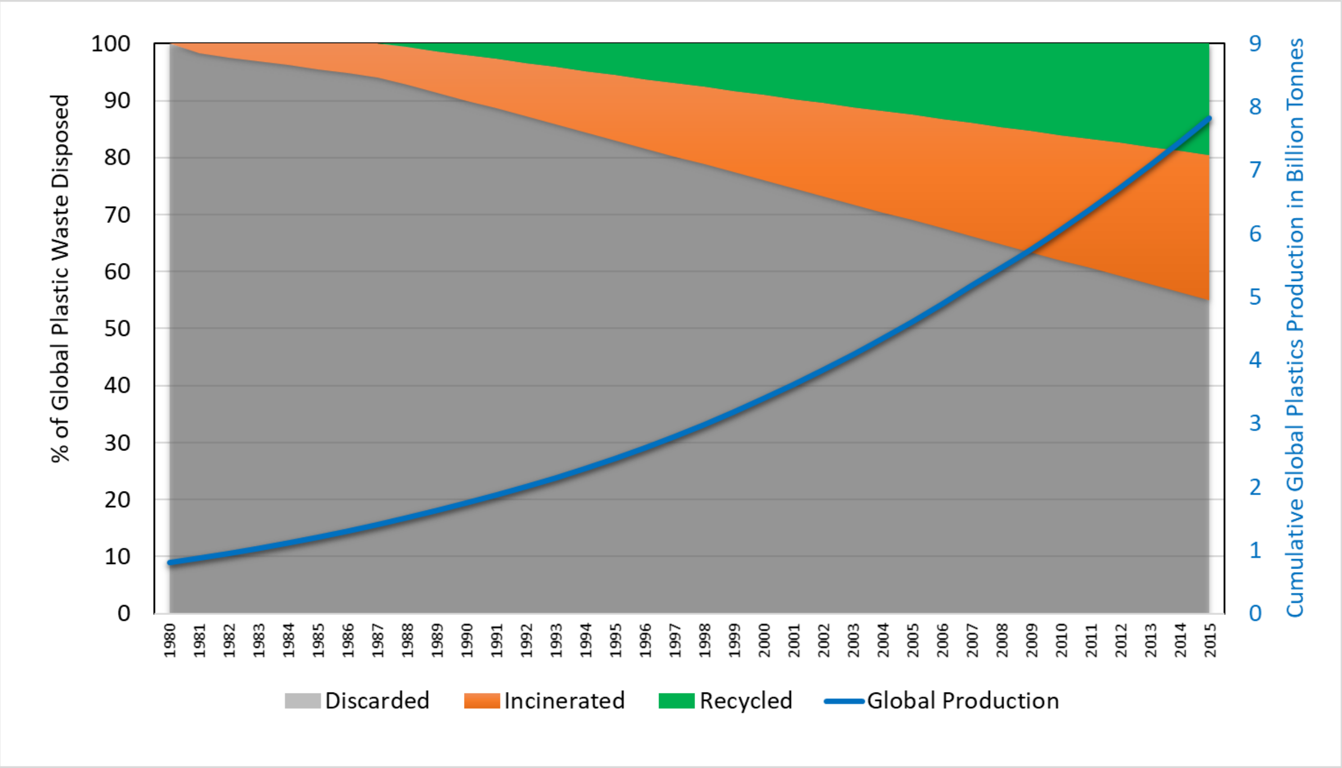


**Figure 2. 1: 1980 – 2015 Cumulative global production of plastics and Estimated share of global plastic waste by disposal method** (15,81)

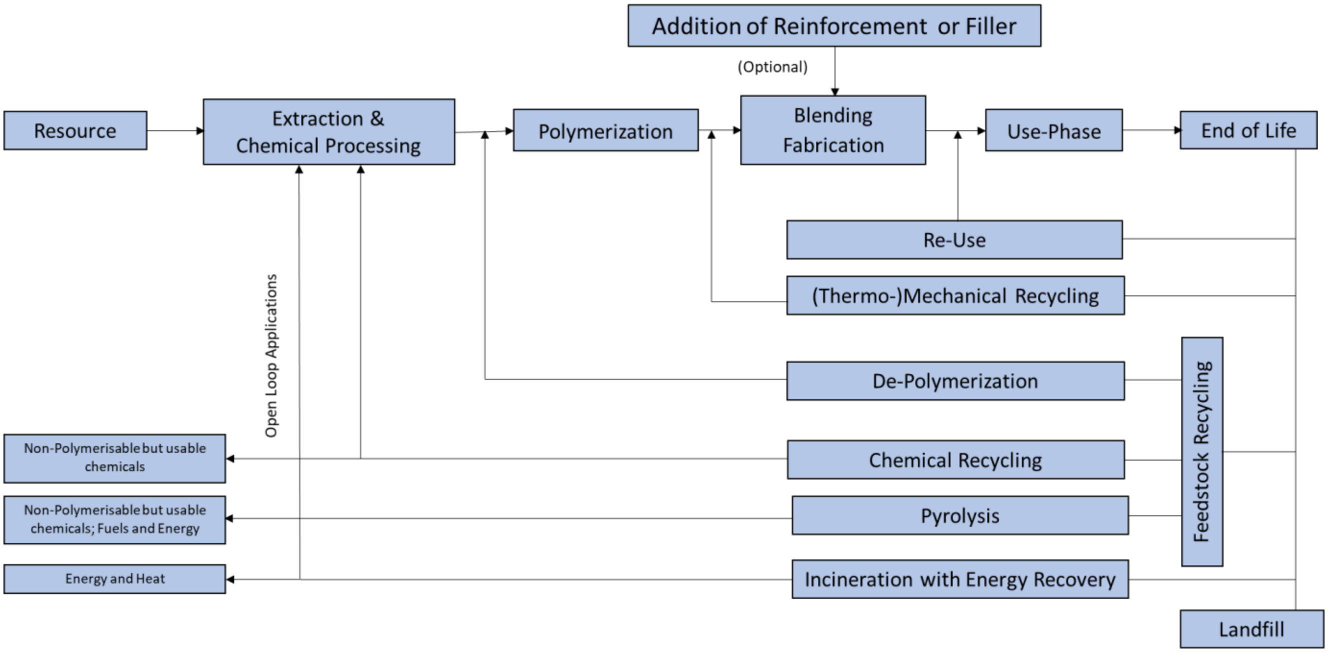


**Figure 2. 2: Various EOL Scenarios for polymeric / plastic wastes (template adapted from reference** (82)**)**

## 2.2 Mechanical Recycling

More than 99% of recycled products are processed through mechanical recycling. Mechanical recycling is a process with a series of unit operations converting discarded plastics to new material or a product without modifying the chemical structure of the polymers (83). Amongst recycling and recovery scenarios listed in Figure 2.2, mechanical recycling is reported to be the most desirable and sustainable solution (27,84). Mechanical recycling allows:

- Re-shaping to new shapes and designs
- Open- & closed-loop recycling: Manufacturing products to various different markets and applications.
- Improvements / modifications in material properties wherever required
- Relatively simple manufacturing process when compared against incineration or chemical recycling (which require intensive engineering controls and abatement systems to control the toxic emissions given off with flue gases (85)).

The benefits of mechanical recycling allow commercialisation of several recycled products such as:

1. Footwear and apparel manufacturing with 71% recycled content predominantly from discarded bottle fraction. Nike reported to have used 3 billion discarded plastic bottles between 2012-2016 (86).
2. Commercial textiles from Teijin polyesters (87) and fleece from Crag hoppers (88) and others (89).
3. Recycled PET foam sheets from Armacell have wide range of end-use applications including structural sandwich panels (90).
4. Commercial plastics lumber for construction (91) and railway sleeper applications (92–94).
5. Compression-moulded recycled plastic sheet replacing chipboard and plywood (95).

### 2.2.1 Mechanical Recycling Process

Mechanical recycling of plastics involves a series of treatments and operations to recycle waste plastics. The general processes involved in mechanical recycling are:

- Waste collection
- Separation and sorting
- Washing and drying

- Grinding to reduce particle size
- Reprocessing to raw material (pelletisation) and / or direct moulding

### 2.2.1.1 Waste Collection

Waste collection and sorting are the centre of waste management systems and determine waste management technique and, in turn, recycled product. Collection methods significantly influence the choice of recycling methodology., i.e mechanical or chemical recycling, energy recovery and composting (96). Pre-sorted collection i.e sorted according to different fractions (plastic/glass/paper/bio-waste fraction) reduces the cost of the recycling program (97). A recent study by Hahladakis et al. (98) compared three types of waste collection scenarios focusing on plastic packaging waste: kerbside collection, household recycling centre ( or civic amenity sites) and bring sites / banks, and found that the contribution from kerbside is significantly higher than the other two other scenarios in the UK. In kerbside collection, co-mingled waste collection was found to be more than 50%, followed by collection of pre-sorted waste (sorted according to glass, plastic and paper) which is around 30%, but pre-sorted waste was reported to be more critical in achieving higher recycling rates (98). Jenkins *et al.* (99) compared a kerbside collection scenario against waste drop off at specified location in 20 metropolitan areas covering both middle and upper-middle income groups focusing on 5 types of waste fraction: glass bottles, plastic bottles, aluminum, newspaper, and yard waste. The percentage of recycled materials was found to be high in the kerbside collection scenario, by around 20%, when compared against drop-off. This finding indicates that the convenience offered by a kerbside collection creates stronger incentives for recycling.

### 2.2.1.2 Separation and Sorting

The purpose of this is step is to separate the plastics according to their type and at a reasonable pace to keep the recycling process economical to compete against virgin plastics. There are several separation / sorting techniques available in practice, and some of them are listed below (100):

I. Manual sorting
II. Automated sorting techniques:
    - Sink-float technique
    - Froth flotation technique
    - Near infrared technique

- X-Ray fluorescence
- Marker system

Manual sorting is the simplest but most labour-intensive sorting technique. Sorting was conducted on the basis of recycling codes, shape, colour, appearance and brand. The sink-float technique utilises differences in material densities to separate mixed waste plastics. The theoretical sink-float scheme is presented in Figure 2.3. However, polymers which are similar in densities cannot be separated in this process (101) - particularly PVC and PET. The froth flotation technique is normally used with materials having similar densities. Polymer mixtures are suspended in a water-surfactant mixture; the polymer fraction which did not adhere to the bubbles will sink to allow separation. This technique allows separation of PVC and PET components (100).

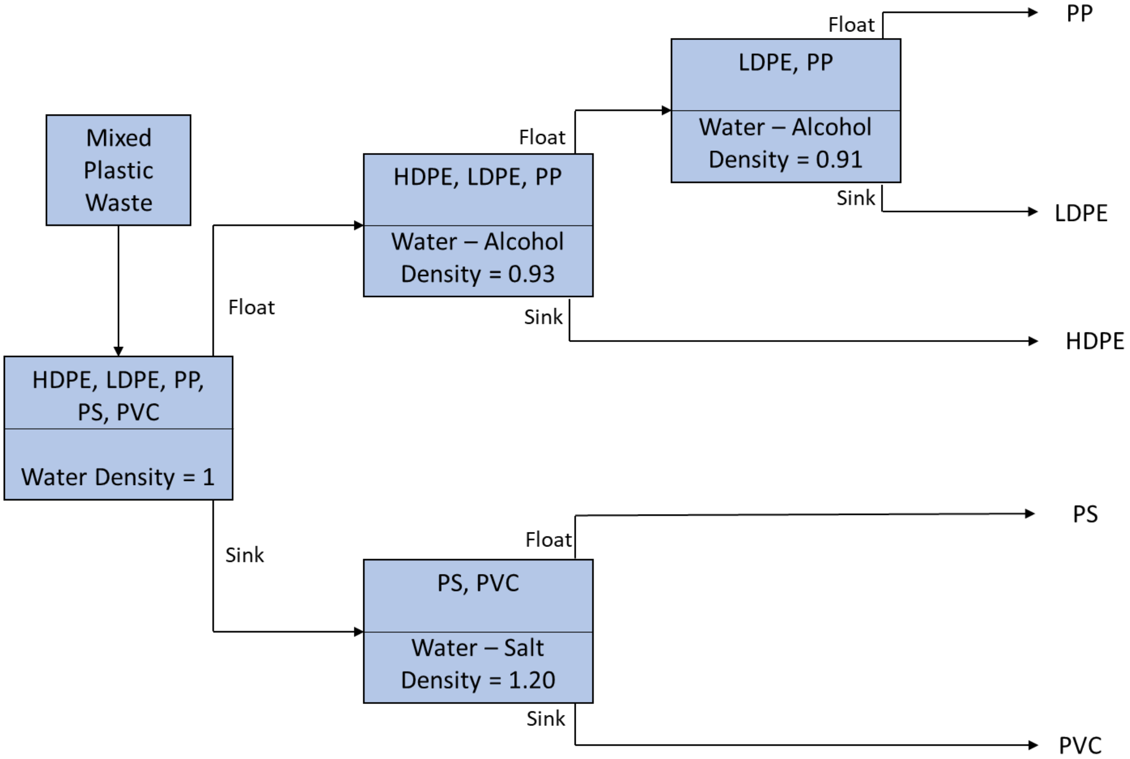


**Figure 2. 3: Theoretical four-stage sink-float system to separate mixed plastic waste** (102)

The near infrared sorting technique uses optical techniques to separate the plastic waste mixture with the help of infrared spectra. Waste plastic is fed in the conveyor belt consisting of a high-resolution optical detector and IR source. The unknown plastic article is scanned and it is compared against the IR library to identify the material. If the unknown spectra matches with the library data, an accurately timed pulse of compressed air is used to shoot the material to the appropriate collection bin (103). A speed of 10 ton / hr and 90-98% purity finds its application in large waste management and material recovery facilities (104).

X-Ray fluorescence technique was mainly developed to identify PVC bottles from PET bottles to achieve PVC-free PET fraction. Chlorine in PVC will generate a secondary X-Ray when the X-Ray is bombarded on the material's surface. The X-Ray generated from the excited chlorine atom is used to identify PVC from PET and an air ejection system is used to separate the PVC fraction (105).

The marker system, developed by Continental Container Corporation, involves marking the packaging with invisible ink to identify packaging according to polymer type, colour, additives and package content. The main limitation of this technique is the overall cost to include the marking system in the packaging. However, this technique is still in the proof-of-concept phase (100).

#### 2.2.1.3 Shredding and Cleaning

Collected and sorted waste plastics are shredded and ground in two stages to achieve suitable particle size for further processing. Typical particle size of grounded material is around 5 x 5mm flakes (101). These flakes are washed to remove dirt, impurities and labels from the plastic fraction, followed by thermal treatment to remove moisture from the plastics (101). Waterless cleaning methods were proposed, but their efficiency, economics, technical and industrial acceptance are still unknown (106,107).

#### 2.2.1.4 Compounding, Pelletisation and Molding

Recycled polymer flakes were extruded in a twin-screw extrusion to obtain pellets which will be used as a raw material to allow fabrication to a new shape. The extrusion of recycled plastic flakes (108):

- Increases homogeneity of the product, through melt mixing
- Helps reduce contamination through melt filtration
- Helps vaporize volatiles through a vacuum segment in the extruder barrel
- Gives provision to add any fillers or additives to stabilise or improve the properties.

Pellets after extrusion are directly mouldable through moulding techniques such as: injection moulding, blow moulding, intrusion moulding, thermoforming and compression moulding.

## 2.3 Incineration with Energy Recovery

This waste management scenario is generally preferred when the quality of waste plastics did not meet quality standards, either because of contamination or waste processing operations such as sorting was not economically feasible. The objectives of incineration are as follows (96):

- Volume reduction: Incineration process generally believed to reduce by around 90% volume and 70-75% weight. This weight and volume reduction have both an economic and environmental advantage.
- Stabilisation: Direct landfill of waste has issues such as gas production and leaching of waste to surrounding areas. Incineration before landfill makes the waste more inert mainly through oxidation burning of organic compounds.
- Energy Recovery: Energy recovered from the incineration of waste materials could be used to generate heat and electricity. This heat and power generation is considered as a source of renewable energy replacing energy and heat from fossil resources.
- Waste sterilisation: This is mostly relevant to clinical waste and incineration destructs pathogens before disposing in landfill.

Organic substances in the waste are combusted in the process of incineration. Organic content in the waste gets burnt when it reaches ignition temperature in the presence of oxygen. The flue gas acts as a carrier of heat energy which gets released after the gas phase combustion reaction (109,110). Depending on the energy content in the waste and oxygen supply, thermal combustion is self-supporting without any need for additional fuels. The different stages of the incineration process are (110):

- Drying and Degassing: Temperature in this phase is around 100-300°C to remove any volatiles.
- Pyrolysis and Gasification: In the pyrolysis phase, organic compounds decompose in the absence of oxygen at a temperature of around 250-700°C. In the gasification phase, at temperatures of around 500-1000°C, organic content in the waste reacts with $CO_2$ and water to transfer organic matter to the gaseous phase.
- Oxidation: In this phase, combustible gases generated in the previous phase oxidize at flue gas at temperatures of around 800-1450°C.

### 2.3.1 Incinerator

A typical incinerator consists of three components or modules and each serve different functions (109) as shown in Figure 2.4.

- Furnace module
- Flue gas treatment module
- Energy recovery system

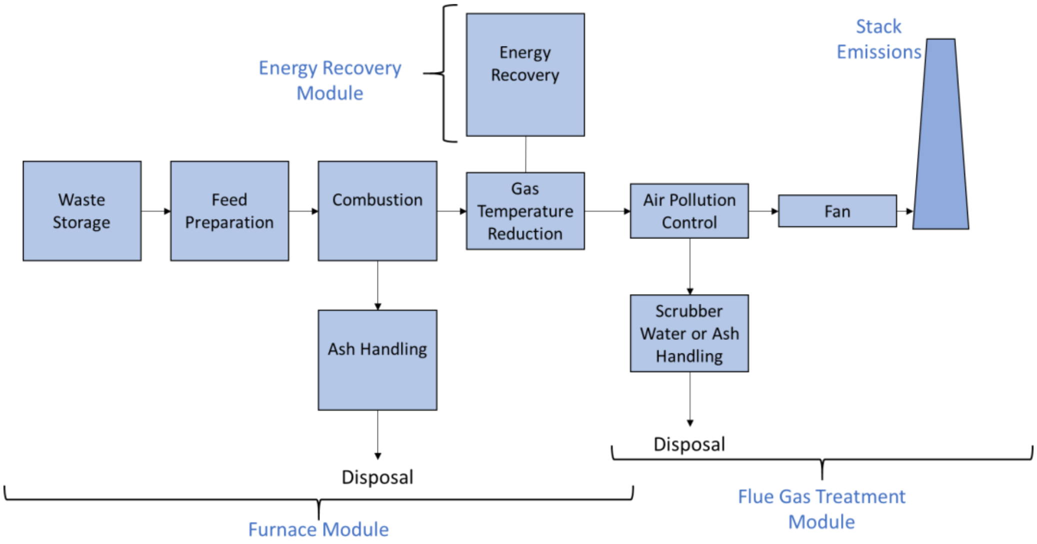


**Figure 2. 4: Schematic representation of a waste incineration facility** (111)

Based on configuration, the incinerator could be one of three main types of incinerators as mentioned below (110):

- Grate incinerator
- Rotary kiln incinerator
- Fluidised bed incinerator

Most of the incinerators in the UK fall under grate or moving grate technology and the remainder are fluidised bed and rotary kiln technology (112).

#### 2.3.1.1 Grate incinerator

Grate systems are used to transport waste to the incinerator. Initially, waste passes through the drying stage to remove and burn volatile compounds. The waste moves further with the grate to fully burn leaving ash in the grate. If temperatures reach above the ash melting point, then it forms slag which will reduce the supply of air, and air is normally injected above the grate for proper combustion (96).

#### 2.3.1.2 Rotary kiln incinerator

The rotary kiln consists of a cylinder, slightly inclined in a horizontal axis, with the provision to rotate around its axis. The cylinder is fed via a hopper. Rotation of the cylinder allows the mixing of waste with the air to achieve complete burnout. Temperatures are around 820 to 1650°C and the residence time is minutes to hours depending on the waste characteristics. Hazardous wastes are destroyed through a post-combustion chamber and additional fuel to enable complete combustion of hazardous gases (96,110).

#### 2.3.1.3 Fluidised bed incinerator

Gases are pumped through an inert granular material (sand) bed to allow the bed to act as a fluid. Gases will help to break the waste material down which will increase the surface contact area of the waste with the air to promote the combustion process. The bed temperature in the fluidised bed is round 650°C and the air above the bed is around 850-950°C. Fluidisation allows good mixing in the reactor to achieve uniform oxygen concentration and temperature distribution resulting in the stable operation of drying, volatilisation, ignition and combustion of waste (96,110,113).

### 2.3.2 Incinerator Emissions

Unlike glass, most polymers are combustible. When polymers are heated continuously with the ignition source, chemical bonds between the polymer molecules will break via thermal degradation to release gas molecules. In the presence of air, if released gases are combustible, the ignition of gases will take place with the subsequent release of heat and more gases. This combustion process will also release carbon particles leading to smoke formation (114). The combustion of hydrocarbon-based polymers gives off more toxic gases than the combustion of bio-based materials like wood. However, some polymers might contain Halogens (chlorine, fluorine and bromine), Nitrogen and Sulfur-based chemical groups which might react with oxygen and nitrogen to give complex toxic gases. The complete combustion of nitrogen-based materials in air will give off some nitrogen-based oxides, carbon dioxide and water. However, incomplete combustion because of poor incinerator design or incorrect combustion temperature, will give off Hydrogen cyanides, nitriles, cyanogen and ammonia along with standard incinerator emissions. Sulfur containing polymers will give off acid on complete combustion. These gases are significantly more toxic than CO or $CO_2$ (114).

As explained above, the incineration of MSW or waste plastics with MSW will generate gaseous emissions and the composition and volume of these gases are dependent on waste composition, combustion temperature, rate of combustion, amount of air / oxygen, residence time and abatement / filter / scrubber mechanism. Considering the toxicity of these gases, all incinerator flue gas emissions are strictly monitored and controlled through the EC waste incineration directive V3.1 (115), and Emission Limit Values (ELV) are listed in Table 2.1. All incineration plants have to be built, designed, equipped and operated to meet ELV (115).

| **Flue Gas Emissions** | **Average Daily Limit** | **Unit** |
|---|---|---|
| Total Dust | 10 | $mg/m^3$ |
| Gaseous and vaporous organic substances, expressed as total organic carbon | 10 | $mg/m^3$ |
| Hydrogen chloride (HCl) | 10 | $mg/m^3$ |
| Hydrogen fluoride (HF) | 1 | $mg/m^3$ |
| Sulphur dioxide (SO2) | 50 | $mg/m^3$ |
| Nitrogen monoxide (NO) and nitrogen dioxide (NO2), expressed as nitrogen dioxide for existing incineration plants with a nominal capacity exceeding 6 tonnes per hour or new incineration plants | 200 | $mg/m^3$ |
| Nitric oxide (NO) and nitrogen dioxide (NO2), expressed as nitrogen dioxide for existing incineration plants with a nominal capacity of 6 tonnes per hour or less | 400 | $mg/m^3$ |
| Dioxins | 0.1 | 1ng I-TEQ / Nm3 |
| Carbon Monoxide | 50 | $mg/m^3$ |
| Heavy Metals: | | |
| Cadmium (Cd) and its compounds | Total of 0.05 | mg/m3 |
| Mercury (Hg) and its compounds | Total of 0.05 | |
| Antimony and its compounds | Total of 0.5 | |
| Arsenic and its compounds | | |
| Lead and its compounds | | |
| Chromium and its compounds | | |
| Cobalt and its compounds | | |
| Copper and its compounds | | |
| Manganese and its compounds | | |
| Nickel and its compounds | | |
| Vanadium and its compounds | | |

**Table 2. 1: Emission limit values (ELV V3.1 2010) of all MSW incineration plant. Excerpt from Article 7 Air emission limit values** (115)**.**

Most of the polymers typically possess high energy values as reported in Table 2.2 (116,117) and these energy values are significantly higher than household refuse, paper and wood. This high energy content differentiates plastic waste from others as it provides stable combustion characteristics to the incineration process along with good energy pay back in the energy recovery phase. Akehata et al. (116) reported that the addition of plastic waste played a significant role in combustion stabilisation without any increase in flue gas pollutants, as shown in Figure 2.5 Akehata et al. (116) conducted incineration experiments in a grate type incinerator (dry scrubbing system containing lime and lime with 3% carbon) with 7%, 14.5% and 24% plastics wastes in MSW and found no significant increase in carbon monoxide and dust. A decrease in $SO_2$ concentration was reported in the study with an increase in the proportion of plastic waste. Polychlorinated dibenzodioxins (PCDD) and Polychlorinated dibenzofurans (PCDF) in crude gas were found to be around 3.7, 3.7, 2.9 ng TEQ/$m^3$ respectively for 7%, 14.5% and 24% of plastics wastes and it was found to be well within German emission specification limits (0.1 ng/$m^3$) after a neutralisation treatment with carbon containing lime.

| Materials | Energy released upon combustion MJ/kg |
|---|---|
| Polystyrene | 46.0 |
| Polyethylene | 46.0 |
| Household refuse | 7-8 |
| Leather | 18.9 |
| Polyvinyl chloride | 18.9 |
| Polymethylmethacrylate | 25.8 |
| Paper | 16.8 |
| Wood | 16.0 |

**Table 2. 2: Calorific values of selected polymeric and non-polymeric compounds** (116,117) **showing high energy content of polymer products**

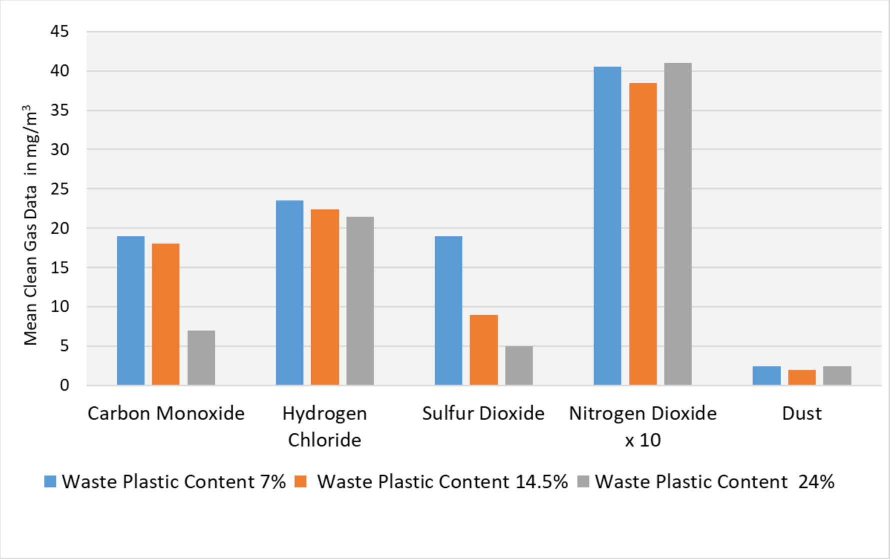


**Figure 2. 5: Flue gas emission: Effect of waste plastics on MSW incineration** (116)

Sovová et al. (118) studied combustion and thermal decomposition of PET under different conditions such as open uncontrolled burning, controlled burning at 500°C and 800° followed by gas analysis using FT-IR, GC-MS and SIFT-MS. The results indicate that gases from open burning and controlled burning conditions resulted in the generation of similar gases. GC-MS analysis indicates that a total of 23 gases were found at 500°C and 21 gases at 800°C including styrene, toluene, naphthalene, benzoic acid, phthalates compounds, and biphenyls. Even though similar gases were found at both temperatures, 800°C incineration seems to be lesser in volume of combustion gases in comparison to 500°C.

Combustion products of polymers, including polyethylene, were reported by Boettner et al. (85) with the study on HDPE at various temperatures. HDPE reported to degrade in a single event at 500-550°C leading to the generation of $CO_2$, water, carbon monoxide, methane, and hydrocarbon products such as ethylene, ethane, methanol and acetaldehyde (119). CO was found to be the only acutely toxic product and increased the generation of hydrocarbons found at incomplete combustion.

Jankowski et al. (120) studied the composition analysis of gases given off when waste plastics were incinerated in a fluidised bed reactor. Results from autothermal incineration are reported in Table 2.3 covering polyethylene, polypropylene, PET and Polystyrene. Autothermal conditions indicate that the reactor will be heated with an external fuel source (LPG in this scenario) until 950°C and the polymer will be fed without any supply of fuel allowing the polymer to self-manage the combustion conditions.

Results indicate that incineration of PS, with the above conditions, generates significantly higher quantities of carbon monoxide, nitrogen oxides hydrogen cyanides and phenylethane.

| Emission | Unit | LDPE | HDPE | PP | PET | PS |
|---|---|---|---|---|---|---|
| $T_{50}$ | °C | 885 | 789 | 847 | 860 | 805 |
| $O_2$ | % | 6.3 | 8.7 | 7 | 8.6 | 6.7 |
| CO | ppm | 2701 | 2421 | 3218 | 1639 | 4246 |
| $CO_2$ | % | 9.5 | 8.9 | 9.4 | 11.1 | 10.9 |
| $NO_x$ | ppm | 29 | 25 | 55 | 13 | 70 |
| $N_20$ | ppm | 0 | 0 | 0 | 0 | 0 |
| HCN | ppm | 30 | 19 | 48 | 11 | 90 |
| VOC | mg/dm$_3$ | 661 | 2194 | 2365 | 197 | 1603 |
| Methane | ppm | 1558 | 1417 | 1762 | 1275 | 1829 |
| Ethene | ppm | 297 | 199 | 292 | 9 | 186 |
| Phenylethene | ppm | 0 | 0 | 0 | 0 | 54 |

**Table 2. 3: Flue gas composition from combustion of commodity plastics** (120) **($T_{50}$ indicates reactor temperature)**

As explained above, emissions are given off when plastics were incinerated and those include Hydrogen cyanide, ammonia, phenol, hydrochloric acid etc. However, with modern waste management plants and gas cleaning systems, most of the emissions are either removed or minimised through a scrubbing system or filter system. Some of the gas cleaning technologies are listed below (96):

- Electrostatic precipitators: mainly to control particles in gases
- Fabric filters: to remove dust
- Wet and dry scrubbers: to control acid gases
- Nitrogen control: to control or reduce nitrogen oxide emissions

More details on this subject could be obtained from (96).

## 2.4 Feedstock Recycling Process

### 2.4.1 Texaco Gasification Process

This is a gasification process to obtain synthesis gas which is a fuel mixture with carbon monoxide and hydrogen as major components. Synthesis gas, produced through a coal or natural gas gasification process, finds application in energy generation (121).

Texaco gasification process, as shown in Figure 2.6, consists of two stages: Liquefication and Gasification stages. The liquefication stage involves thermal cracking or depolymerisation of mixed plastic waste (MPW) to get synthetic heavy oil and condensable / non-condensable gas fractions. Synthetic oil and condensable gas are injected into a gasifier and gasification was carried out at 1200-1500°C along with oxygen and steam to obtain synthesis gas. Non-condensable gas fraction is used as a fuel in the liquefication stage. Synthesis gas will be refined through multiple cleaning and drying stages to remove HF and HCl. Chlorine emitted from PVC fraction cleaned through ammonia washes yielded Ammonium Chloride ($NH_4Cl$) in a saleable form. Sulfur residue from mixed plastic wastes (MPW) is pure and saleable along with Ammonium Chloride (122,123).

Treating mixed plastic wastes in the Texaco gasification process yields:

- 350,000 $Nm^3$ (Nm3 indicates Normal Cubic Meter measured under the standard conditions of 0 degrees Celsius, and 1 atmosphere of pressure) of clean Synthesis Gas which is a mixture of Carbon Monoxide and Hydrogen from 150 tonnes of plastic waste.
- Pure Sulfur and Ammonium Chloride meeting saleable industrial standard specifications.
- Fines with quality similar to Fly Ash from incineration plants.
- Vitrified slag with a quality sufficient enough to be used as secondary building material specification.

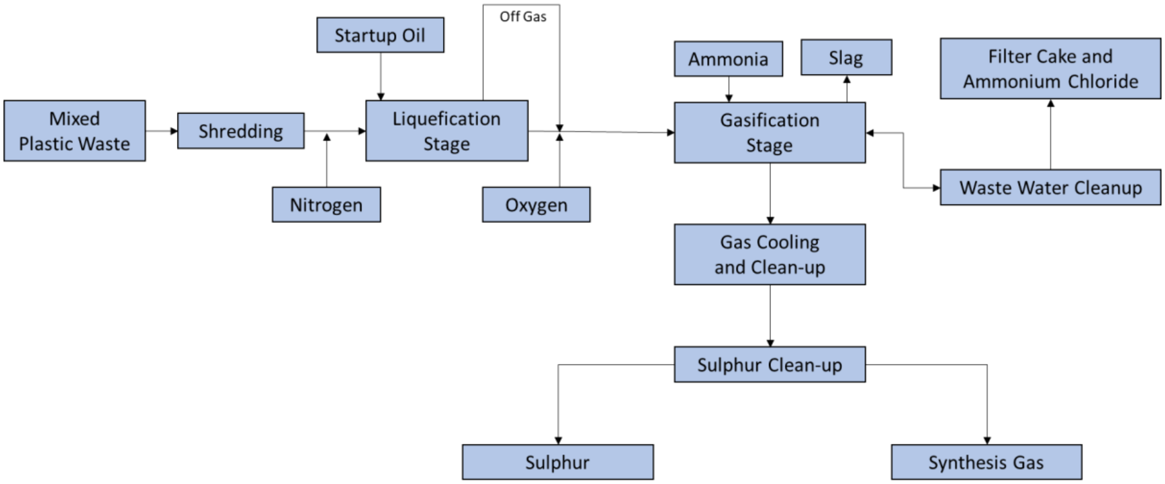


**Figure 2. 6: Texaco Gasification Process of treating mixed plastic waste: Schematic Representation** (122)

### 2.4.2 BP Polymer Cracking Process

This is a fluidised bed cracking process developed by BP along with industrial partners. This process was demonstrated in a pilot plant at BP's Grangemouth site in Scotland with the name 'Project POLSCO'. Size-reduced plastic waste fraction is fed into a heated fluidised bed reactor. Plastics are cracked at 500°C in the absence of air, resulting in vaporisation of fluidised gas. HCL emission in the fluidised gas from PVC waste is neutralised through the scrubbing system and metallic emissions from additives are either trapped in the bed or captured through a cyclone. Purified fluidised gas is cooled and distilled to obtain hydrocarbon feedstock. Hydrocarbon is recovered in two stages: as light (40%) and heavy fraction (80%), as heavy fraction is recovered as a wax under 60°C. 85% of the output leaves as a hydrocarbon liquid and the remainder as a gas. Gas has a high concentration of ethylene and propylene monomers which could be polymerised to useful polymers (123).

The hydrocarbon from this process is reported to contain 10 ppm of Cl with low levels of Pb, Cd and Sb with tests indicating that all hydrocarbon fraction is usable in a refinery. Even though the refinery operation demands under 5 ppm of Cl content, BP confirmed that it is acceptable, as high dilution is possible in the petrochemical operations(122).

### 2.4.3 BASF Conversion Process

This process was originally designed to process waste from DSD (Duales System Deutschland) collection and was in operation between May 1994-1996 with the capacity of 15,000 ton / year at the Ludwigshafen pilot plant and with the plan to build a large-scale plant to process 300,000 tons per year by BASF. However, the project was dropped in 1996 with closure of the pilot plant as the long-term waste supply could not be guaranteed to justify the plant's operation costs (123).

Metal free, shredded, deagglomerated mixed plastic waste fraction is only suitable for this process. Plastic waste is exposed to a multi-stage melting and reduction process. The first stage involves dehalogenation to avoid corrosion to the plant. The HCl generated in the process is transferred to a HCl production plant for processing the resulting saleable product. After dehalogenation, plastic waste is heated to 400°C, to crack polymers into varying chain lengths with 60-70% as oils and the remainder as gases (122).

- Naptha generated in this process is treated in a steam cracker to recover ethylene and propylene monomers.
- High boiling oils are processed to obtain synthesis gas or conversion coke.
- Residue in this process is likely to have maximum of 5% minerals.

### 2.4.4 Solvolysis Depolymerisation Process

This process deals with exploiting chemical reactions to reverse polymerisation through the breaking of C-O and / or C-N bonds. Materials like PET, PU and Nylons were made via step growth reversible reactions which are exploited in this method to obtain basic chemicals / monomers through glycolysis, hydrolysis and methanolysis (124). This technique has not proven successful in complex and mixed plastic waste streams. Solvolysis examples are given below:

Glycolysis was used to depolymerise PET to its raw material. This technique was used by Goodyear to depolymerise, purify and repolymerise along with virgin PET resin and launched REPETE polyester resin (125). However, this process was not successful enough to obtain food contact approval.

The methanolysis process involves treating PET at high temperature and pressure to obtain dimethyl terephthalate (DMT) and ethylene glycol (EG) which could be re-used to polymerise these monomers back to polymers, as shown in Figure 2.7. PET through this technique was reported to have obtained food contact approval and successfully used as a blend with virgin PET in Coke and Pepsi bottles (124). Methanolysis was reported to be used by commercial manufacturers including Eastman, Hoechst, and Dupont (126). Methanolysis also received some recent interest in setting up a chemical recycling plant to manufacture DMT and EG feedstocks (127).

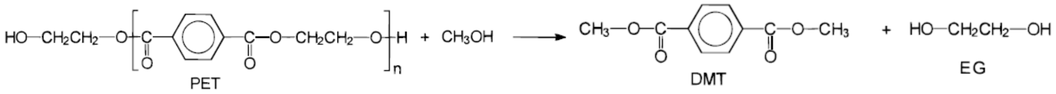


**Figure 2. 7: Methanolysis of PET to produce dimethyl terephthalate (DMT) and ethylene glycol (EG)**

The hydrolysis technique, patented by Amoco and others, was reported to have successfully developed a PET depolymerisation process to obtain Terephthalic acid (TA) and ethylene glycol (EG). More details on this technique could be obtained from literatures (124,126).

Comparison of these PET depolymerisation methods reported by Aguado and Serrano et al. (80) are summarised as follows:

- Hydrolysis seems to be a less energy intensive process with 20-30MJ/kg, whereas glycolysis and methanolysis are in the range of 40-60 MJ/kg.
- Low quality plastic waste feed specification favors glycolysis and hydrolysis as contamination did not seem to have a major influence in the process.

- Safety, health and environment aspects seems to be a concern for most of the techniques: methanolysis uses superheated methanol demanding stringent operating procedures. A corrosive medium in hydrolysis produces liquid effluents with inorganic salts demanding chemical disposal and effluent treatment operations.
- Process economics are reported to be better for glycolysis in small-medium volumes (around 100,000 tonnes). Methanolysis demands large capital investment and is of interest only at higher volumes.
- Combined glycolysis – hydrolysis was also reported to get the benefits of both methods.

Solvolysis techniques were extensively reported in Polyurethane and Nylon, and more details on these materials could be obtained from literature (80,124).

### 2.4.5 Thermolysis Depolymerisation Process

Chain-growth polymers that were synthesised via free radical or ionic reactions are depolymerised to their monomers or basic chemicals through thermolysis. Polystyrene (PS) and Polymethylmethacrylate (PMMA) are reported to obtain their monomers through thermal decomposition, whereas most of the other polymers (Polyolefins) lead to mixture of various decomposition products of varying chain lengths with a low concentration of monomers. Product distribution seems to be dependent on conditions like temperature, feedstock, type of reactors and their operation methods (80).

The thermolysis process involves the heating of plastics waste in the absence of oxygen to produce liquids, gases, residues, chars and inorganic fillers. Pyrolysis does not involve combustion or burning, but a set of thermal reactions to obtain various decomposition products. Some of the possible reactions pathways and products are as follows (124):

- Depolymerisations to monomers in PMMA and PTFE
- Fragmentation of polyethylene and polypropylene backbone to oligomers of various lengths and moieties producing alkanes, olefins and diene fragments.
- Combined fragmentation and decomposition in Polystyrene (PS) and Polyisobutylene (PIB).
- Extraction and elimination of inorganic moieties in Polyvinylchloride (PVC) producing cyclic charred material.

Kaminsky et al. (128) conducted a pyrolysis study of plastic waste containing polyolefin (75%) and polystyrene (25%) in a fluidised bed reactor at 730°C yielding 35% pyrolysis gas and 44% aromatic oil.

Pyrolysis gas was found to be composed of methane, ethane, ethene and propene. Aromatic oil consisted of benzene, toluene, xylene, ethylbenzene and styrene as major components. A pyrolysis study conducted by Donaj et al. (129) on mixed plastic waste reported that at 650°C pyrolysis yielded a heavy fraction containing heavy oil, wax and carbon black whereas a 730°C pyrolysis temperature yields lighter or gaseous fraction. A recent review on pyrolysis of plastic wastes summarised the following (130):

- Polystyrene was found to be the best material to yield 97% liquid oil. This high yield in polystyrene is because if its low thermal stability.
- LDPE, HDPE and PP was found to produce 93.1%, 84.1% and 82.1% yield respectively and use of catalyst is expected to increase the yield.
- Optimum temperature for liquid oil seems to be around 500-550°C with the potential to reduce to 450°C with the help of catalyst.

## 2.5 Recycled Plastics and Property Modification

Polymers are generally designed and formulated to meet the demands of one service life including both melt processing and use phase. Polymers, after their useful life, enter waste streams and get re-processed. As reported by Karlsson et al. (74), structures and properties in their second lives are affected by following aspects:

- Composition and degree of mixing: this includes contamination from other polymeric and non-polymeric materials. The presence of other materials introduces incompatibility affecting the molecular interfaces and end properties.
- Degree of degradation: this includes degradation from multiple melt processing and use-phase environmental factors such as UV rays. For instance: use phase / service life affects properties and applications in styrene based materials (131), whereas multiple processing affects end properties in polypropylene based materials (132).
- Presence of low molecular weight compounds.

Several routes have been attempted to improve the properties of recycled materials so as to make them suitable for various application needs. Some of them are as below:

- Mixing with virgin plastics: this is one of the common applications exploited by research institutions and industries (133,134). Recently, Borealis introduced polyolefin grades containing 25% and 50% recycled fractions under the brand name ‘NAV101-117’ through Ecoplast (135).
- Compounding with fillers (136–138): this methodology is a simple and well exploited technique to improve the properties of recycled plastics. Fillers such as talc and calcium carbonate are widely used with recycled plastics and also commercialized with trade names Borcycle (139) and Ravaplen (140).
- Addition of stabilisers and compatibilisers (134,141): Compatibilisers were aimed to use with mixed waste plastic to improve its interaction and compatibility to attain improved properties. Compatibilisers for mixed plastic waste are available commercially (142).
- Addition of fibrous reinforcements (143): this mainly involves the addition of glass fibres to manufacture thermoplastic composites to improve the mechanical and thermal properties of recycled plastics.

Selected studies covering the effect of fillers and fibres in properties of recycled plastics will be covered in the following section as they are most relevant to this project.

## 2.6 Review on reinforced recycled plastics

As mentioned above, some of the possible reasons affecting the properties of recycled plastics are (74):

- Contamination and incompatibility from foreign polymers and fillers
- Degradation either due to multiple processing cycles or because of use-phase
- Presence of low molecular weight materials

Simulated recycling (via multiple processing) and simulated use-phase (via accelerated thermo-oxidation) studies on PP and HDPE materials by Stromberg et al. (132) indicate that multiple processing did not have a significant effect on tensile strength and elongation. The authors indicated that the modulus value in PP dropped by 12% (from ~975 MPa to ~850 MPa) after 6 processing cycles and there was no change in HDPE. Errors bars in the graphs indicate the spread is around 50 MPa in both the first and second processing cycles indicating that the drop in modulus is not significant when we consider natural variation in the testing and / or sample preparation process. Studies on simulated use-phase indicate that thermo-oxidative ageing significantly affected elongation at break on PP material as values dropped from 300% to 30%. Thermo-oxidative degradation does not seem to affect tensile strength or modulus in PP. HDPE was reported to be stable without any change in mechanical properties.

Similar simulated recycling experiments were carried out in the same research group by Karlsson et al. (131) on HIPS indicating that multiple processing steps did not affect mechanical properties more significantly than use-phase thermo-oxidative degradation. % elongation decreased from 60% to 10% after six days of thermo-oxidative ageing whereas 9 reprocessing cycles decreased elongation only to around 45%, indicating that use-phase degradation is a dominant factor in affecting properties of styrene-based polymers. The following observations could be derived from simulated degradation studies (131,132):

- Degradation, either through melt processing or through use-phase, could be clearly indicated through % elongation.
- Tensile strength and elongation are not significantly affected much in all three PP, HDPE and HIPS.
- Youngs modulus was found to have some negative effect in PP owing to multiple processing cycles and no effect in HDPE and HIPS.

The objective of the addition of reinforcements and fillers in recycled plastics in this research is not just to compensate for the loss of mechanical properties, but also to significantly improve the tensile strength and modulus properties so as to be able to use in a structural or semi-structural application and literature related to this objective will be reviewed in this section.

Xanthos et al. (144) conducted extensive analysis on the effect of compatibilisers and reinforcement on mixed plastic wastes (MPW). The plastic wastes selected were composed of 80% polyethylene, 5-8% PET and the remainder is the mixture of PP, PVC and PS. The study included evaluation of MPW in three scenarios: 1) MPW, 2) MPW with 20% glass fibres and 3) MPW with 20% glass fibre and compatibiliser. Maleic anhydride was used as the compatibiliser. As shown in Figure 2.8, the addition of glass fibre reinforced MPW, increased the tensile strength by around 230% and flexural modulus by 150%, there was only marginal improvement in impact strength. However, the addition of a compatibiliser increased tensile strength by another 17% and impact strength by 50%. Flexural modulus decreased a little which could be due to compatibilisation and an increase in ductility. As mentioned in the study (144), glass fibres were providing physical compatibilisation between different polymer phases and reinforce-ability increased when compatibiliser was added - improving chemical interaction and finer phase morphology.

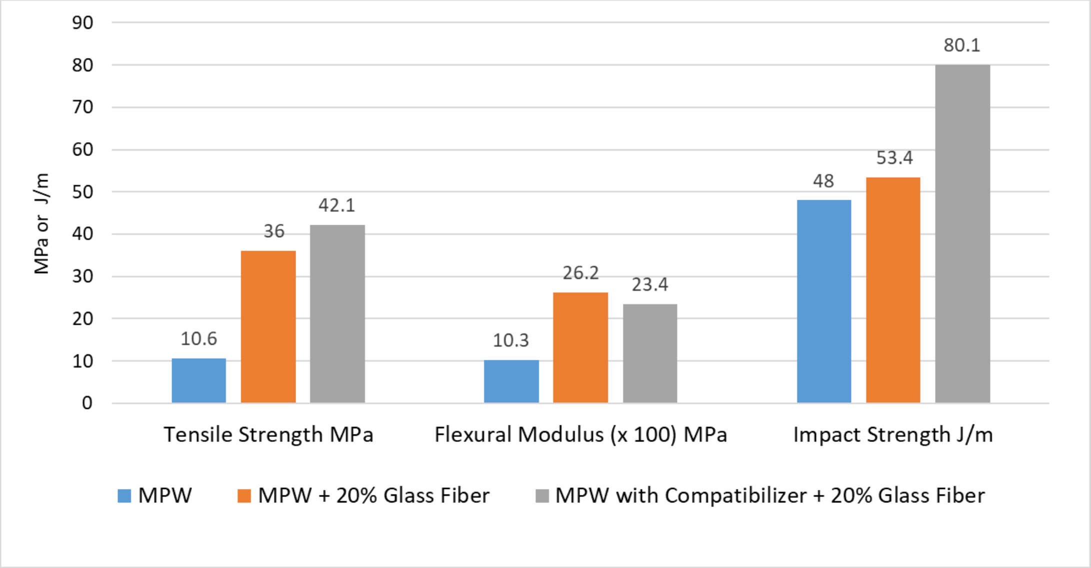


**Figure 2. 8: Effect of glass fibre and reinforcement with MPW. Data adapted from Xanthos et al.** (144)**. Flexural modulus represented as factor of 100. Fibre fraction is in wt%.**

Xanthos et al. (145), conducted another study, similar to that above, with MPW and reinforcement but with two different types of compatibilisers (Maleated SEBS and Maleated HDPE) in combination with 15% chopped glass fibres. Results indicate that maleated HDPE seems to provide better results owing to better adhesion of glass fibre and matrix. However, finer morphology with maleated SEBS is a sign of improvement in polymer-polymer compatibilisation with MPW matrix, but with no significant improvement in impact strength MPW and filled-compatibilised thermoplastics, contradicting the previous study (144).

Mantia et al. (146) studied and published effect of fillers on recycled plastics. The matrix used in the study was PET with HDPE and evaluation was done at 10, 20 and 40% glass fibres. As shown in Figure 2.9, at maximum fibre loading (40 wt%), tensile modulus increased by 95%, tensile strength by 150%, impact strength by 109% and Heat Deflection Temperature (HDT) by 100%. % elongation before modification was 1.3% indicating incompatibility of PET and HDPE blends. However, after adding glass fibre, property improvements are significant, indicating the existence of adhesion between the matrix and the fibre. Mantia et al. (146) also compared glass fibre against Wollastonite in which glass fibre provided significant improvements to MPW in tensile strength and HDT. However, at the same fibre weight fraction, Wollastonite provided higher elongation than glass fibre.

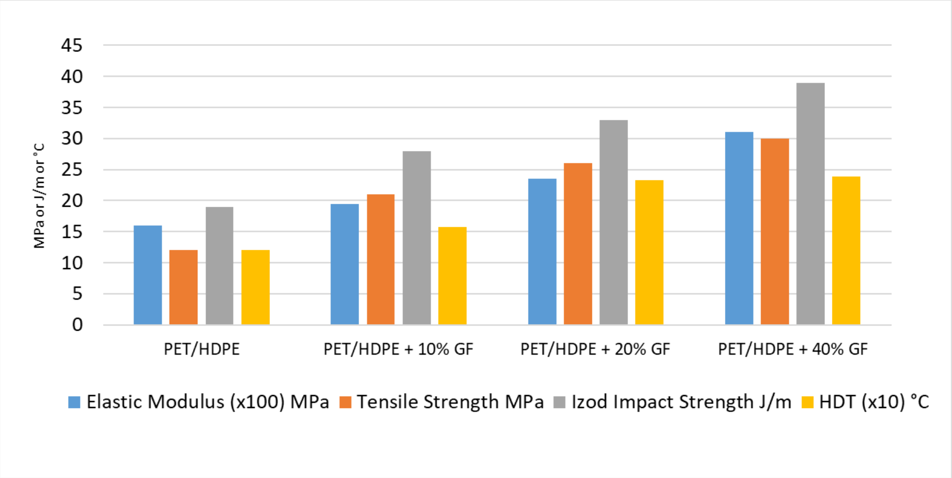


**Figure 2. 9: Effect of glass fibres on thermal and mechanical properties of PET HDPE blends. Data adapted from Mantia et al.** (146)**. Elastic modulus and HDT are represented as a factor of 100 and 10 respectively. Fibre fraction in wt%.**

Sahnoune et al. (147) conducted extensive studies on mixed plastics consisting of HDPE and PS predominantly, from detergent bottle waste and milk bottle waste respectively. Studies involved the evaluation of the effect of calcium carbonate filler and compatibiliser (SEBS and SEBSgMA) in mixed plastic waste where recycled HDPE (RHDPE) and recycled PS (RPS) are major and minor components respectively. Results are summarised in Figure 2.10. Strength, modulus and impact strength indicate that HDPE is a semi-crystalline, soft and tough material, whereas PS is an amorphous, rigid and brittle material. When RPS was added to RHDPE, modulus increased by 20% (when compared against RHDPE) without any change in strength. The addition of 20% CaCO3, increased modulus by another 20% but impact strength dropped by 20%. SEBS compatibiliser increased the interaction between HDPE and PS, whereas SEBSgMA increased the interaction between both HDPE-PS and HDPE-$CaCO_3$ resulting in lowering the impact strength of the composite. Optimum mechanical performance was obtained with 4% SEBS in the blend where modulus increased (when compared against recycled HDPE/PS blend) by 20%, impact strength increased by 66% without much significant impact in strength. Calcium carbonate seems to improve mechanical properties, but improvement are significantly lower than glass fibre reinforcement (144) which could be because of aspect ratio and shape factor.

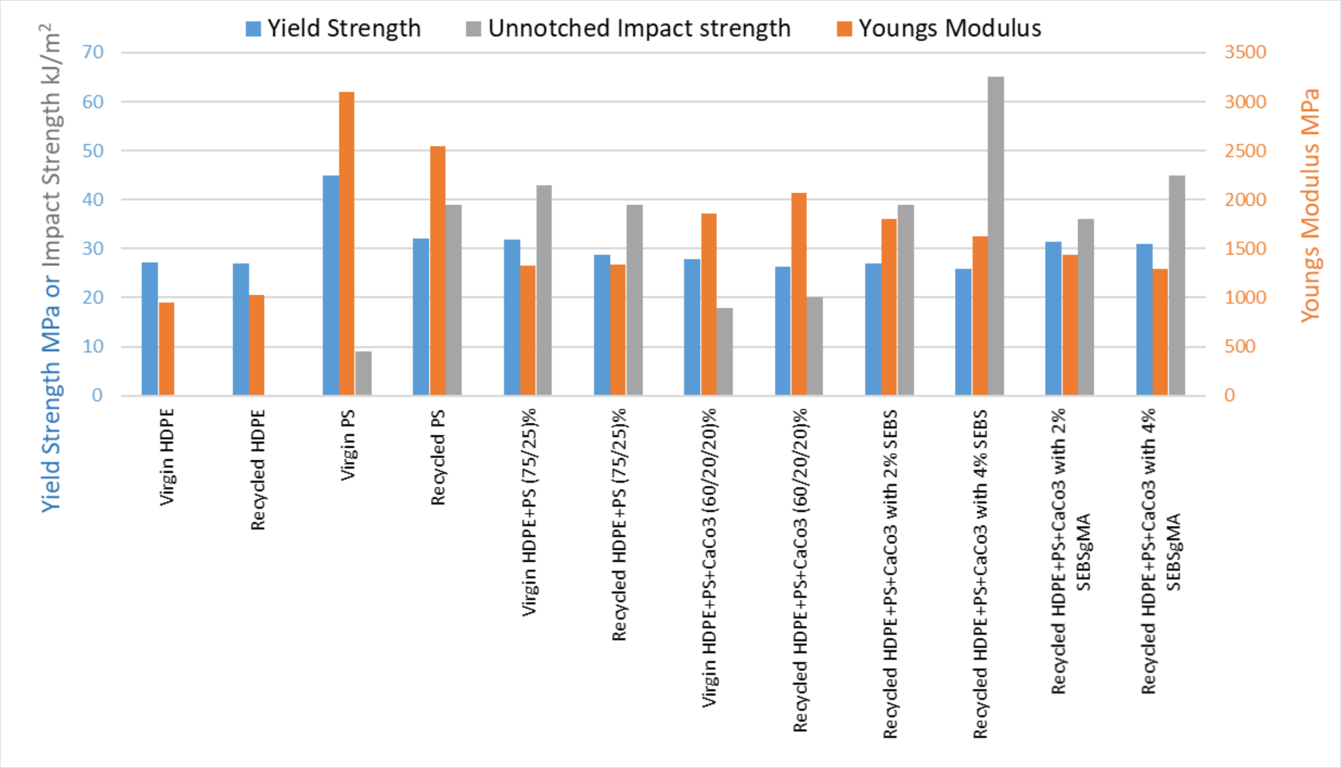


**Figure 2. 10: Effect of calcium carbonate in recycled HDPE / PS blend shown along with virgin HDPE, virgin PS. Effect of compatibilisers (SEBS and SEBSgMA) are included. Data adapted from Sahnoune et al.** (147) **and composition is based on wt%.**

Putra et al.(138) conducted similar studies on post-consumer plastic packaging waste (70-80% polyolefins and 20% PET and PS) by adding various mineral fibres and fillers. Glass fibres, Talc, Wollastonite and Gypsum were the fillers utilised with silane and without silane treatment. As reported (144–146), glass fibre gave significant improvements in tensile strength (30% increase) and modulus (300% increase). Talc seems to improve the properties by 20% on strength and 170% on modulus. Silane treatment on Talc seems to increase tensile strength and modulus by around 12-13% when compared against untreated fillers. However, Wollastonite found to provide relatively better improvement of 20% when treated with silanes. As reported by Lino et al.(143), There are several other similar studies on fillers and fibres on mechanical property improvement with recycled plastics and some of them are listed in Table 2.4.

| Description | Author | Reference |
|---|---|---|
| Recycled fibreglass and wood flour as filled to plastic waste | George et al. | (148) |
| Recycled HDPE and PP with Kraton compatibiliser and fibreglass | Adewole et al. | (149) |
| Glass fibre reinforced PP and EPDM from recycled bumpers | Oh et al. | (150) |
| Compatibilised Nylon and PP blend reinforced with glass fibre. Nylon and PP from carpet recycling | Hagberg et al. | (151) |
| Recycled PET with glass fibre and evaluating the effect of hygrothermal ageing | Pegoretti et al. | (152) |
| Laminate made of recycled PET with woven glass mat and chopped strand mat through compression molding process | Cantwell et al. | (153) |
| Recycled PET with short glass fibres | Rezaeian et al. | (154) |

**Table 2. 4: Studies related to reinforced recycled plastics**

## 2.7 Plastics recycling and Life cycle assessment

### 2.7.1 History of LCA

Life cycle assessment-type studies began in the early 1960s when concerns over population in relation to the shortage of raw materials and energy resources (155). After the first oil crisis in 1973/74, when oil prices increased from $5 to $12-15 a barrel (156), increased the awareness of importance of conservation of natural resources. Following this in 1969, researchers at the Coca-Cola company conducted comparative analysis of different beverage containers and quantified the usage of natural resources and environmental emissions from the manufacturing process of each container. This led other companies in the USA and Europe to conduct similar analysis under the name ‘Resource and Environmental Profile Analysis (REPA)’ in America and ‘Eco-balance’ in Europe (155).

But the oil glut in the early 1980s decreased the interest towards environmental concerns which combined with the reversal of energy efficiency and renewable energy policy (157). However, solid waste management became a major issue in 1988 which led LCA to re-emerge as an environmental and methodological tool to evaluate environmental impacts (155). From 1988, LCA studies have been published, particularly in plastics recycling and solid waste management. Some of the selected LCA studies are summarised below in two sections:

- Waste recovery
- Recycling

### 2.7.2 Waste Recovery

This phase involves collection of waste from the point of generation, transporting the collected waste and dropping it off in a recycling centre or transfer station. Larsen et al. (158) measured fuel consumption for 14 different types of collection schemes in two municipalities in Denmark. This involved measurement from the first point of collection to the final stop. The collection schemes evaluated by Larsen et al. (158) and are relevant to our study are shown below:

- City Centre
- Apartments buildings outside City Centre
- Rural areas
- Drop off points
- Bring-in system via private cars
- Pneumatic systems

Eisted et al. (41) estimated the GWP from data on collection methods compiled by Larsen et al. GWP estimation was based on the provision and combustion of fuel. Both fuel consumption and GWP data are presented in Figure 2.11. Among kerbside collections, the impacts are lowest for apartment blocks and the city centre with GWP less than 10kg-$CO_2$ Eq / tonne which could be related to high population density and / or high waste generation rate within a small area. Among household waste collection, the rural side has the highest (around 26kg $CO_2$ Eq per tonne) impact which could be due to the long distances between collection points. The collection of drop-off bottle and paper fractions are in the range of around 13-15kg $CO_2$ Eq per tonne indicating that it is better than rural collection routes. The bring-in system is the highest (200 kg $CO_2$ Eq per tonne) among all types of collection methods when waste quantity is just 15kg per trip of 5-10km. But when weight is in the range of 100kg, the impact of the bring-in system comes down to around 30 kg $CO_2$ Eq per tonne. It is interesting to find both of the modern collection methods, pneumatic collection techniques are significantly higher (44-47 kg $CO_2$ Eq per tonne) than waste collection impacts from standard apartment blocks which could be due to the associated systems consuming energy to operate fans and vacuum systems.

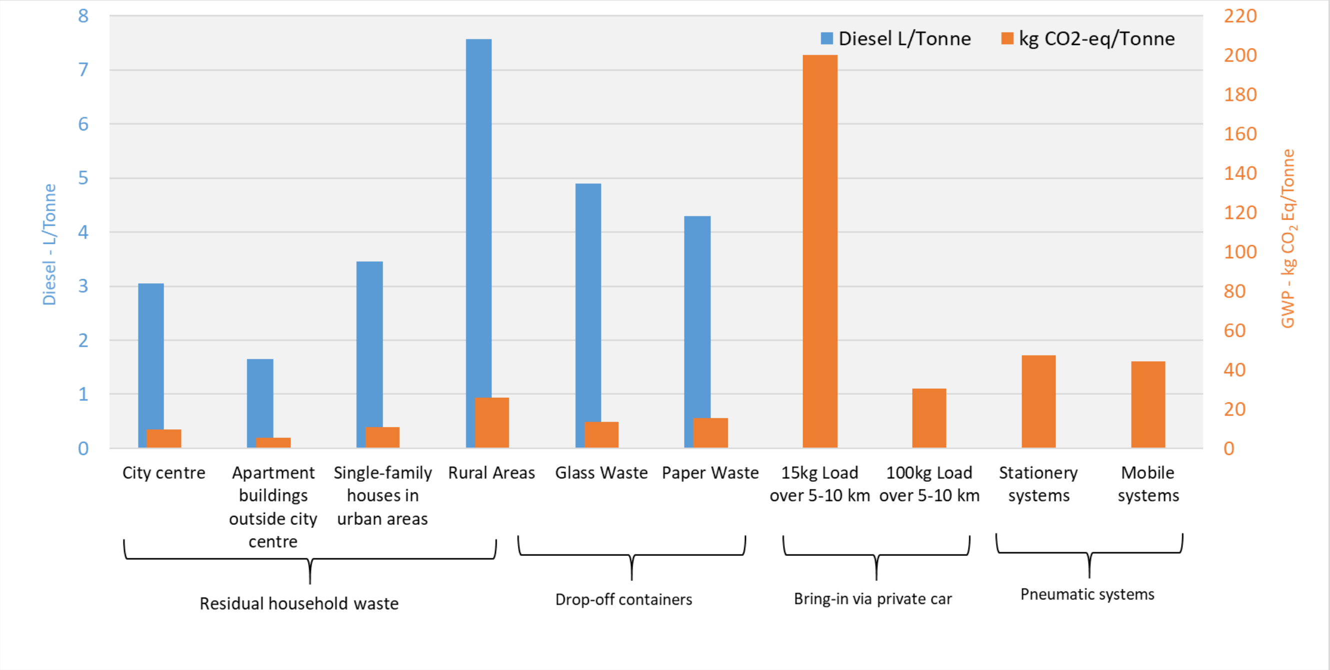


**Figure 2. 11: Fuel consumption and GWP of various collection methods (**(41,158)**), comparing carbon emissions between various waste collection methods. Fuel consumption for bring-in and pneumatic systems are not available.**

Ian Boustead, analysed energy flows (shown in Figure 2.12) (28) in recycling in relation to recycling and recovery rate. The study (28) considered energy flows in closed-loop recycling and open-loop recycling with and without yield losses. Boustead evaluated recycling from the perspective of energy savings relating to recovered and recycled fraction and total system energy savings. As shown in Figure 2.12, recycling and recovery will lead to energy savings until a certain recovery ratio which will be the maximum energy (shown as F2) savings of the whole system. This could be related to diesel consumption data from Larsen et al. (158). Efficient waste collection is from apartment blocks (around 1.6L per tonne) and after waste collection from apartment blocks, to increase recovery rate, waste from other areas (example: rural areas) needs to collected which has higher diesel consumption (rural areas 7.6L/tonne). After reaching a maximum energy saving fraction (F2), energy flow will increase and reach F1 - which is a break-even point beyond which recycling and recovery would not save any energy to the whole process and it will be vice-versa. However, this energy flow did not consider plastics ending up in water streams and oceans.

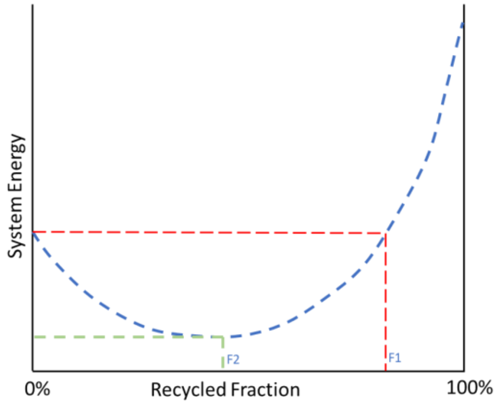


**Figure 2. 12: Energy flow and recycled fraction** (28)

### 2.7.3 Recycling

As discussed in Section 2.2, sorting is one of the critical operations to separate polymers according to their types. Among existing sorting techniques, NIR and sink-float methods are widely used (39). Energy consumption including various unit operations are shown in Table 2.5. NIR machines are available with volumes controlled by the width of the conveyor belt. The energy consumption value does not include accessory equipment like compressors, which are intermittently used to direct the plastic to the correct bin. Energy consumption of sorting varies between 6.69 to 11.6 MJ / tonne based on data reported by Shonfield et al. (39). However, data from Arena et al. (27) reported as 0.16 and 0.11 MJ/kg which is equivalent to 270 MJ/ton.

| Recycling Unit Process | Tonne/h | kW | MJ/h | MJ / Tonne | Additional Details | Source |
|---|---|---|---|---|---|---|
| | Throughput | Power Consumption | Power Consumption | | | |
| NIR Sorting (A) | 0.861 | 1.6 | 5.76 | 6.69 | Power consumption from accessory equipments (eg. Compressor ) are not included | Shonfield et al. |
| NIR Sorting (B) | 0.861 | 1.3 | 4.68 | 5.44 | Power consumption from accessory equipments (eg. Compressor ) are not included | Shonfield et al. |
| NIR Sorting (B) | 3 | 6 | 21.6 | 7.20 | Power consumption from accessory equipments (eg. Compressor ) are not included | Shonfield et al. |
| NIR Sorting (B) | 5 | 15.5 | 55.8 | 11.16 | Power consumption from accessory equipments (eg. Compressor ) are not included | Shonfield et al. |
| Pre-Treatment Operation (max rating) | 2 | 630 | 2268 | 1134 | Inclusive of Shredding Eddy current metal removal, Air-separatation and Density separation | Shonfield et al. |
| Density Seperation | 4 | 28 | 100.8 | 25.20 | Inclusive of 2 x pumps @ 3 kW and 2 x vibration sieves @ 11 kW | Shonfield et al. |
| Drying per tonne | NA | 32.5 | NA | 117 | Based on 4 t/h throughput with drying requiring 85 KW/t plus 15 kW per additional tonne | Shonfield et al. |
| Extrusion | 0.25 | 120 | 432 | 1728.00 | | Shonfield et al. |
| Sorting of PE and PET | | | | 270 | Technology not reported | Arena et al. |

**Table 2. 5: Recycling unit process energy consumption** (27,39) **covering NIR sorting, density separation and extrusion**

The difference could be because of a difference in machine capacities, or data from Arena et al.(27) could have included all related power consumption from compressors and acceleration belts.

LCA studies on plastics recycling have been widely reported and some of the selected studies are compiled in Table 2.6.

Commissioned by WRAP (Waste & Resources Action Programme), Shonfield et al. (39) conducted extensive LCA analysis on mixed plastic wastes covering 16 different scenarios of plastics waste management. Scenarios include:

- Landfill
- Incineration with energy recovery,
- Conversion to solid derived fuel (SRF) in cement kilns
- Combination of mechanical recycling with pyrolysis (BP Polymer Cracking Process)
- Combination of mechanical recycling with pyrolysis (Ozmotech)
- Redox agent in Blast Furnace
- 10 Mechanical recycling scenarios of individual fraction, differentiated by sorting methods.

The assessment ranked landfilling and incineration as the worst choices to manage plastic waste and recommended the mechanical recycling scenario. Shonfield et al. (39) considered sensitivity analysis by including quality of recylate and substitution ratio against virgin plastics. Considering global warming, mechanical recycling will not be beneficial when recycled plastics do not replace at least 70% of virgin plastics. This indirectly means that the waste management system and technology should be sufficient enough to generate high quality plastic wastes.

One of the earliest and extensive exercises in LCA of the plastics recycling subject was by carried out by Hyde and Kremar (37) covering 12 scenarios under 4 waste management options, which are listed as follows:

- Feedstock recycling
    - ❖ HTV Gasification process
    - ❖ KAB hydrogenation process
    - ❖ Blast furnace process
    - ❖ BASF process
    - ❖ SVZ gasification process

- Energy Recovery
    - Co-combustion of plastic waste in MSWI
    - Fluidised bed combustion
- Mechanical Recycling of film and bottle fraction
    - Bottle manufacturing from DSD bottle fraction
    - Film manufacturing from DSD film fraction
    - Cable conduits from film fraction
- Mechanical Recycling of mixed plastic fraction
    - Manufacturing of palisades
    - Manufacturing of Construction Fence Base

The GWP and energy profile of all these scenarios are compiled and reported in Figure 2.12. Kremar et al. (37) stated that all of these scenarios are not directly comparable as analysis is based on different end products. Results presented in the original study consist of multiple impact categories which makes comparability even more complex. Considering energy consumption and GWP, mechanical recycling scenarios were found to be environmentally favourable which is because of the assumption that recycled plastics are replacing virgin plastics in various substitution ratios. Cable conduit is based on a 1:1 substitution ratio against virgin plastics, and, along with its low material loss, makes it the best scenarios followed by bottle manufacturing as second best because of its high material losses. 0.7:1 substitution ratio makes film manufacturing environmentally unfavourable.

Replacing wooden products out of mixed plastic waste is commercially exploited and it is found to have scored reasonably better environmental credentials only when the ‘replacing wooden palisade with lifetime’ ratio is 2 i.e polymeric palisades are expected to last twice as long as their wooden counterpart. Environmental credits from feedstock recycling were found to perform better than replacing palisades, as the products from feedstock recycling (through blast furnace and BASF process) are expected to replace chemical feedstocks. Products from BASF process are Naptha, Aromatics, coke and conversion gas, whereas plastics waste is expected to replace heavy oil in the reduction process.

| Ref | Functional Unit | Impact Categories | Substituting Material | Comment |
|---|---|---|---|---|
| (38) | Comparison of railway sleepers made of recycled plastics and wood considering life time ratios | Global warming potential | Recycled plastics replacing treated wood | The comparison of life cycle of wooden sleeper and plastic sleeper indicates that recycled plastic sleeper can potentially save 628 and 66kg $CO_2$ per km in Brazil and German conditions |
| (159) | Comparison of softwood lumber with WPC lumber at 1000 board feet. | All major impact categories reported by CML method | None | Wooden lumber found to be more environmentally favourable than WPC |
| (34) | The industrial waste plastics were recycled (made of rice husks and cotton linters) and compared against virgin plastics. | Non-renewable resource consumption, global warming, acidification and eutrophication | Virgin Plastics | The operations such as shredding, cleaning, drying were accounted in the recycling process except waste collection. Recycled plastic composites found to be environmentally friendlier than virgin plastics. |
| (39) | Various scenarios such as landfilling, feedstock recycling, pyrolysis, as fuel for cement kilns, ER and MR are compared | All impact categories suggested by CML methodology | Results indicate that landfilling and incineration with energy recovery are the worst choices to manage plastic wastes and recycling as one of the preferred scenarios. | Quality of recycled plastics was considered as a part of sensitivity analysis. Assessment estimated that when MR could not replace at least 70% of virgin plastics then feedstock recycling or SRF in cement kilns to be considered so as to minimize favour lower GWP. |
| (84) | Recycling one kg of plastic wastes to get (a) Recycled plastic flakes, (b) Energy (C) hydrocarbons (via hydrocracking and pyrolysis). | Fossil Fuel Consumption, Global Warming, Solid waste generation, air emissions,<br>water consumption | (a)Virgin plastics, (b) heat and electricity, and (c) hydrocarbons | The scenarios compared are mechanical recycling, incineration with energy recovery, low temperature pyrolysis, hydrocracking and its combinations |
| (37) | Various process of recycling such MR of films and bottles, MR of mixed plastic wastes, Energy recovery and Feedstock recycling were compared in the basket of products methodology. | Energy consumption, water consumption, global warming, acidification, eutrophication, and solid waste. | For feedstock recycling: synthesis gas, heavy oil (in blast furnace), petrol, steam cracker feed, hydrogenated bitumen, natural gas, benzene, coal coke naphtha, methanol, crude oil, electricity, crude oil. For energy recovery: heat and electricity. For MR: Virgin Plastics, blow moulded bottles, cable conduit, wooden palisades and concrete construction fence bases | Mechanical recycling scenario replacing virgin plastics with substitution ratio of 1:1 found to perform better than energy recovery and feed stock recycling. In MR, cable conduit found to consume minimum energy and emit less emissions than other products (Concrete products, wooden products, plastic bottles, and films) |
| (160) | The following scenarios are compared (a) MR with NIR sorting, (b) MR with solvent based sorting, (c) Pyrolysis, (d) energy recovery, e) landfilling | Non-renewable resource consumption, global warming, nutrient enrichment, photochemical oxidation, and acidification | Virgin plastics for MR scenario, wood for mixed plastic wastes, virgin hydrocarbons for pyrolysis, district heating for incineration scenario | The study concludes that plastics recycling can be environmentally sound if it can able to replace virgin plastics and if properties of recyclate is not good then incineration with energy recovery is considered to be a second-best option |
| (29) | MR was compared against landfilling | Global warming, acidification, and nutrification | Virgin Plastics | The results indicate that recycling of plastics found to have significant environmental benefits rather than economic benefits. |

**Table 2. 6: Selected LCA studies on plastics recycling**

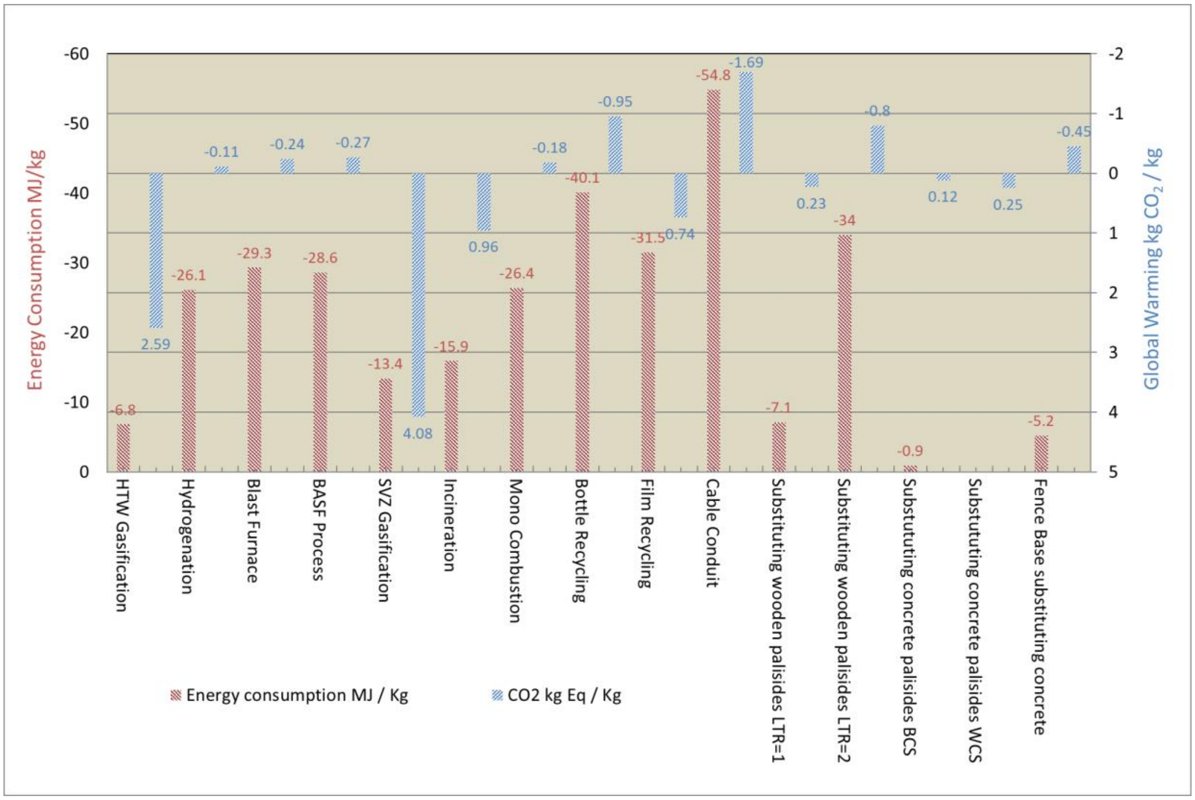


**Figure 2. 13: Energy consumption and global warming potential of various recycling options. Data adopted from Kremer et al.** (37)

Ana et al. (38) compared recycled plastic railway sleepers in Germany and Brazil. The functional unit considered is one kilometre of railway track consisting of 1,852 railway sleepers with 20-30 years lifetime for wood and 50 years for recycled plastics. With Brazilian conditions, recycled plastic sleepers were found to save 628 kg $CO_2$ Eq per km of railway track when compared against wooden sleepers. With German conditions, the carbon savings when using recycled plastics sleeper is 66 kg $CO_2$ Eq per km. This difference in result between Germany and Brazil is because of sustainable forest management and increased lifetime of wooden sleepers in German conditions. Bolin et al. (159) compared alkaline copper quaternary (ACQ) treated wood against wood plastic composite lumber. The functional unit considered is functional 1000 board feet (Mbf) and per representative deck surface per year of use. It is reported that replacing wooden lumber with WPC would cause 14 times more use of fossil fuels and 3 times more emission of $CO_2$. Mixed results were reported when recycled plastic replaces wooden products as reported by studies from Ana et al. (38), Kremar et al. (37), and Bolin et al. (40).

Arena et al. (27) compared five different scenarios of plastic waste management including landfilling, part landfilling and part incineration, incineration, and 3 mechanical recycling scenarios with variations in handling of process waste. The waste plastics considered in this study are predominantly PE and PET. The LCA study included collection, sorting, grinding, washing, and drying. Out of six scenarios, mechanical recycling with incineration of process waste was found to be beneficial. Craighill et al. (29) conducted similar LCA studies in plastics recycling but included economic assessment along with LCA. Even though recycling been favoured for its environmental credentials, economically it did not yield positive results which is reportedly mainly because of the waste collection phase affected by low density and high volume of plastic waste - limiting the amount of waste carried in each trip. Similar studies (26,34,84,160) have been published in LCA and plastics recycling, but mostly they are similar to studies described in this section apart from minor variations.

## 2.8 Conclusion

Based on literature review, knowledge gap related to this research are summarised as below:

- Correlation of composites made of recycled polymers with LCA
- Effect of performance attributes of recycled polymer systems & their composites on LCA
- Effect of End of Life of polymer wastes on products developed from recycled polymers
- Environmental performance of recycled polymers and their composites based on various end use applications and markets
- Effect of various impact assessment methods on polymer recycling methods and products based on recycled polymers.

# Chapter 3: Reinforced Recycled Plastics and their Applications

## 3.1 Introduction

Consumption of plastics is increasing every year. As shown in Figure 1.1 in the introduction section, there has been a significant growth in plastics production in last four decades which has resulted in huge accumulations of plastic waste. Recycled plastics seem to have a demand based on the fact that they are cheaper than virgin plastics. Virgin plastics price volatility challenges the recycling plastic market and affects the consumption of recycled plastics. In 2015, oil prices dropped to $20 a barrel which made virgin plastics price near equivalent to recycled plastics (161), removed any price incentive for using recycled plastics, and decreased the demand for choosing recycled plastic for many applications. On the other side, the European plastics manufacturers association committed to reach the target of 60% recycling rate by 2030 and 100% by 2040 to address current plastic pollution through recycling and circular economy (162).

Some of the common applications of recycled plastics were products such as bin bags, paint trays, buckets, single use bags, ground reinforcements, bollards, non-food grade packaging, etc. Among these, very few are high-value engineering applications. These selected applications limit the consumption of recycled plastics and do not motivate recycling to achieve recycling targets. The concept behind this chapter is to focus on manufacturing high-value composites based on recycled plastics and evaluate its potential in civil engineering and automotive applications.

### 3.1.2 Weight Reduction and Automotive Applications

The automotive sector is one of the volume-driven sectors. This is facilitated by constant evolution, including efficient engines, navigation, safety and electrification. As shown in Figure 3.1, 38 million passenger cars were produced in 1998 and this was almost doubled by 2018 (163). A wide variety of materials are used in the automotive industry including steels, aluminium, glass, rubbers and plastics. Plastics and fibre-reinforced plastics were around 6% in the 1970s but this has tripled by 2010-2018 reaching around 18% (164) in automotive applications. The increase in the proportion of plastics and reinforced plastics in the automotive industry are due to factors such, including weight reduction (light weighting), ease of manufacture, damage tolerance, damping and allowing versatile and complex designs. This makes the automotive segment (4.9 million tonnes) the third largest plastic consumer in Europe following packaging (19.9 million tonnes) and building and construction (9.8 million tonnes) (165). Apart from volume, the automotive industry uses a variety of polymer materials such as polypropylene, polyethylene (LD/HD), polystyrene, ABS, PA, PMMA, PC and these provide various options for recycled polymer to replace virgin polymers considering its properties and performance limitations.

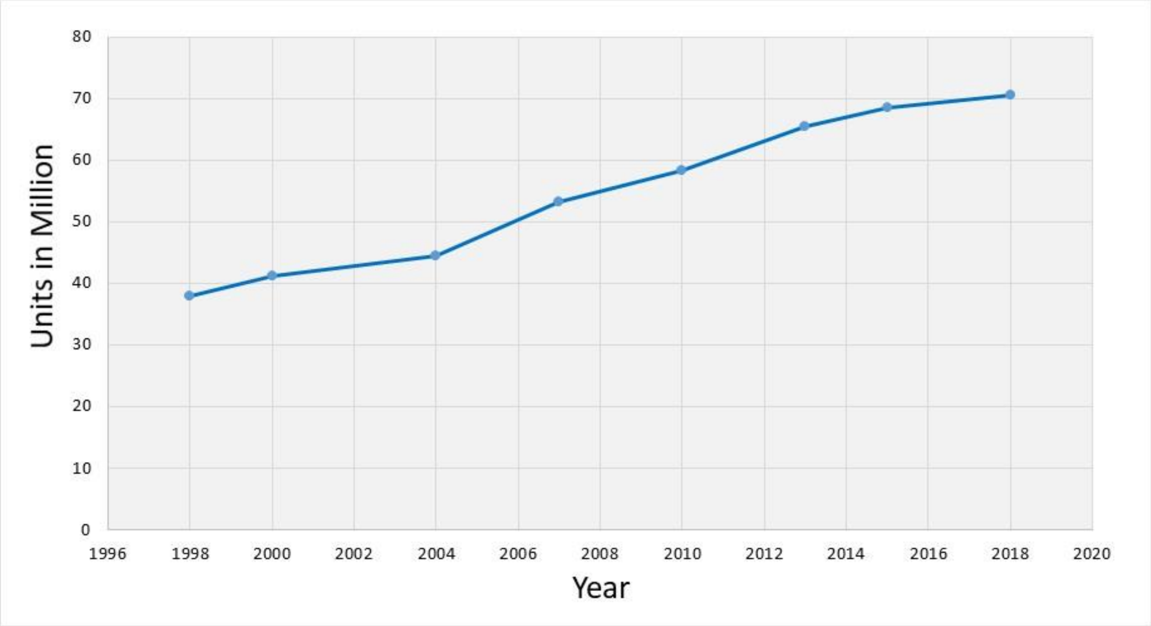


**Figure 3. 1: Passenger Car Production Statistics from 1998 to 2018** (163)

LCA studies have been reported comparing various recycling operations. However, no LCA study has reported on composites developed from recycled plastic and evaluated for various applications. In this chapter, Life Cycle Assessment was conducted on composites from recycled polymers so as to reduce the 'environmental impact' than the conventional product meeting the same functional criteria.

## 3.2 Life Cycle Assessment

The Simapro V 7.2.3 (166) LCA package was used to compare glass fibre and flax fibre reinforced recycled polymers with virgin alternatives. This study stays between 'Streamlined' LCA and 'Full Scale' LCA (78,167). The data collected for study are collected from: peer reviewed literatures, industry reports, LCA databases, estimated from semi-empirical models and qualitative guidelines, etc.

### 3.2.1 Goal

This is to quantify and compare the environmental impacts associated with fibre reinforced composites made from virgin and recycled polymers in two different applications considering their mechanical performance requirement:

- Civil and Infrastructural Applications
- Automotive Applications

### 3.2.2 Functional Unit

Fibre reinforced composites made from virgin and recycled polymer (Polypropylene (PP)) were compared at equal mechanical performance (elastic modulus) with two different reinforcements: flax fibre and glass fibre.

### 3.2.3 Scope

What is included in this study?

- Acquisition and manufacturing of reinforcements
- Virgin plastics and its manufacturing
- Recycled plastics and recycling operation
- Use phase impacts included in automotive application and excluded in civil engineering applications.
- End of life of composites

What is not included in this study?

- Manufacturing and manufacturing differences of the actual components as they are going to be the same for both scenarios
- Transport between material manufacturing, component manufacturing and EOL locations as it is assumed to be similar in both the scenarios.
- Emissions from incinerating flax fibre, owing to non-availability of LCI and complexity of carbon sequestration, allocation and carbon cycle.
- Life time difference between composites made of virgin and recycled polymer

## 3.3 Life Cycle Inventory

System boundaries are shown in Figure 3.2.

### 3.3.1 Fibre Reinforcements

There are several fibrous materials such as glass, carbon, Kevlar, basalt, flax and hemp fibres available to be used as a reinforcement in composites (168). Glass fibres and Flax fibres are chosen for this study because of their properties, versatility and their varied applications. Glass fibres are well known in the composites industry and are widely available and exploited in various applications such as thermoset composites, thermoplastic composites, adhesives and insulations. Flax fibres are natural fibres and are available in Europe and widely considered in academic research and industrial applications.

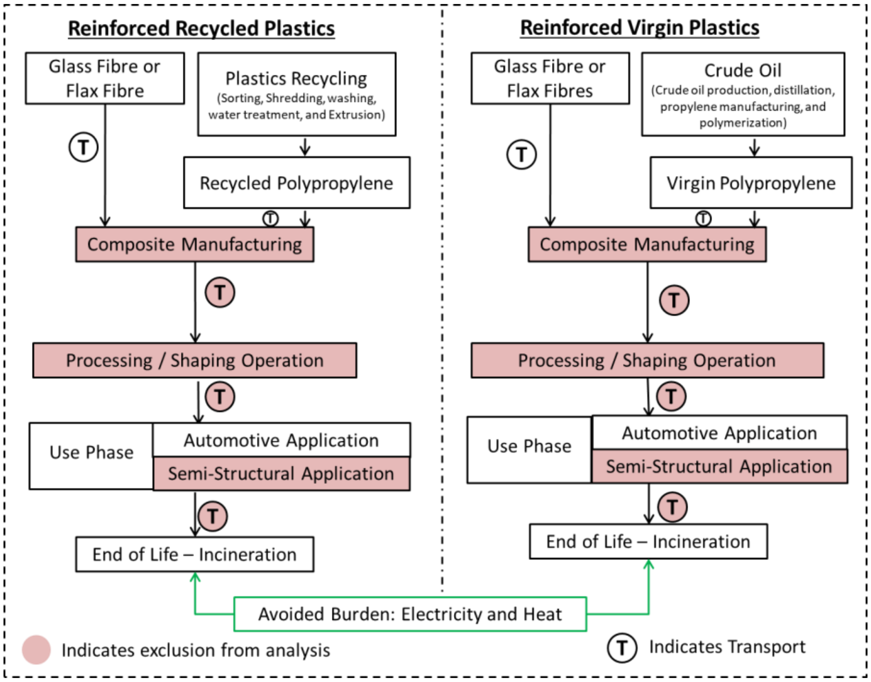


**Figure 3. 2: System Boundary showing unit process covered in the analysis**

#### 3.3.1.1 Flax Fibre Life Cycle inventory

**Background on Flax Fibre Growth and Cultivation**

Both Linseed and Flax fibre have the same species name 'Linum Usitatissimum' as they are very similar apart from some minor differences (169):

- Linseed is predominantly grown for seed and the latter for its fibre
- Linseed is smaller and denser than flax

The process steps involved in flax cultivation are seed sowing, crop protection, harvesting, rippling, retting, breaking, scutching, hackling and spinning (170,171) and European flax production flow chart (172) is shown in Figure 3.3.

### Seed Sowing

Flax for fibre is generally sown in the UK around April as the crop needs a frost-free temperate environment and is generally sown in high density to discourage branching. Flax is generally resistant to pests and parasites but general precautions against these were normally undertaken.

### Harvesting or Pulling

For good quality fibre flax, the plant is allowed around 3-4 months growth phase to attain maturity. Maturity is generally assessed through the colour (yellowish brown) of the stem and the degree of defoliation. After attaining maturity, the plant is pulled out of the ground with a pair of circular belts. Pulling helps retain the length of the fibre.

### Rippling and Retting

Rippling is the operation where seed heads are removed from the plant. This operation is carried out with metallic combs. Retting helps to release the shorter fibres. Retting is a natural process where organisms such as fungi and bacteria produce enzymes to dissolve the binder which holds primary fibres to the stem. Retting can be conducted in couple of possible routes 1) Water Retting 2) Dew Retting. Water retting is a less preferred option owing to its labour-intensive operation and environmental concerns. Fibres are dried after the retting process.

### Scutching

This is the operation where the outer straw layers were separated to release inner fibre. Hand scutching is normally done in a wooden scutching board where flax stalks were scraped and beaten with a wooden scutching tool to release fibres from the rest.

### Hackling

This is the process where fibres are separated from each other which are bound together. This process is carried out using a hackling tool as shown in Figure 3.4. Fibre bundles are pulled through metal combs to separate short and coarse fibres from long fibres. This process is repeated until finer filaments are obtained. The by-products of this operation are shorter and coarser tows which are spun into tow yarn.

| | **Qty in Kg / Hectare** |
|---|---:|
| **Input:** | |
| Ammonium Nitrate | 121 |
| Triple superphosphate | 65 |
| Potassium chloride | 100 |
| Lime | 666 |
| Seed | 115 |
| Fuel (Diesel) | 68 |
| | |
| **Output:** | |
| Dry, green flax stems | 6000 |
| Seed | 600 |

**Table 3. 1: LCI data of flax fibre** (173)

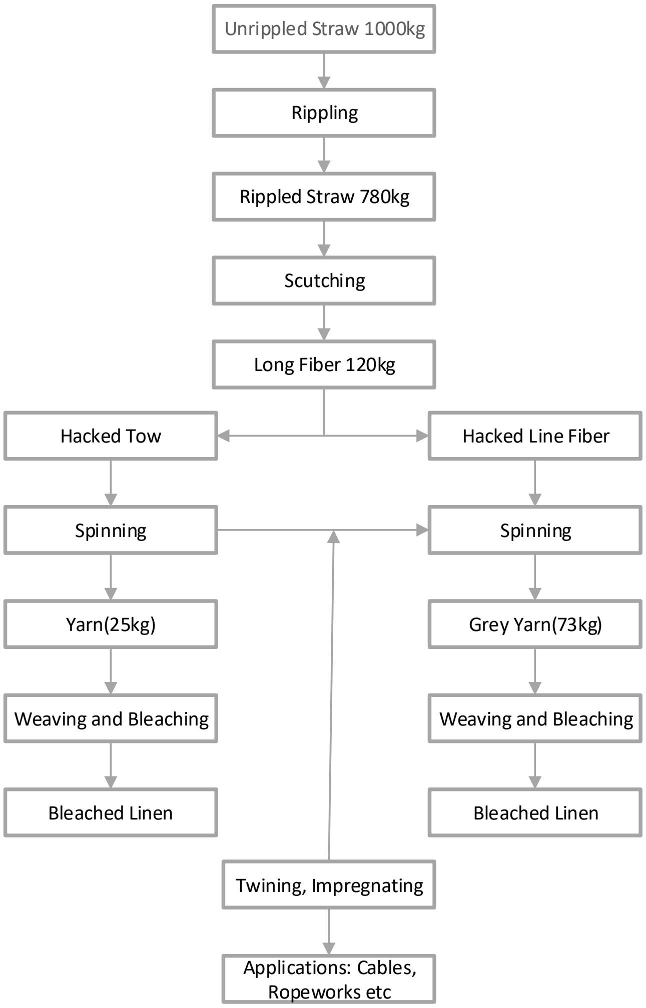


**Figure 3. 3: European flax production flow chart showing various operations involved in flax fibre production** (172)

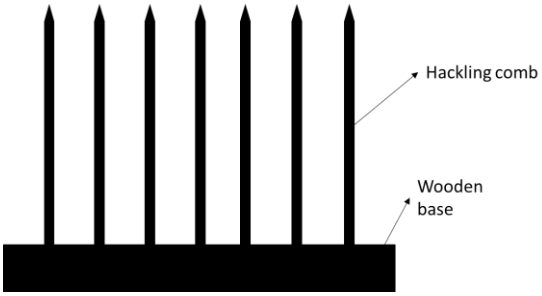


**Figure 3. 4: Hackling tool** (174) **– schematic representation**

Flax Life Cycle Inventory Data

This study does not include a field study of the flax fibre planting and growth and they are adopted from Turunen et al. (173) and Nilmini et al. (175) and are summarized in Table 3.1. Mass balance and yield data can be found in Appendix 1.

### 3.3.1.2 Glass Fibre Life Cycle Inventory

Glass fibres are one of the most common and economical reinforcements widely used in polymer and composites industries. Based on composition, glass fibres are broadly classified as E-Glass, S-Glass or Quartz. E-Glass, a general-purpose grade, is common and mainly used in composite industries. S-Glass is a specialty grade and expensive, it is particularly used in electrical applications and reported to retain its properties at high temperatures. Quartz is an ultra-pure silica glass widely used in demanding electrical applications owing to its low dielectric properties (176). The inventory for this analysis is adapted from the Eco-invent database library in the Simapro Software.

**Manufacturing Process** (168,177)

Glass in glass fibres is composed of silica, alumina, calcium oxide, magnesium oxide, and other inorganic oxides. The composition of E and S - Glass are shown in Table 3.2 and the process flow chart in Figure 3.5 (177). The first step in the manufacturing process involves the melting and blending of raw materials in a furnace at 1500°C to achieve a molten glass with optimum viscosity. The molten glass from the reservoir is fed to a platinum bushing which contains several hundred holes. Molten glass is initially gravity fed through these holes but then wound onto a drum at very high speed. The diameter of the fibre is dependent on feed tank, hole diameter, winding speed and viscosity. E-Glass fibre is typically around 10-16µm diameter.

| Ingredient | E-Glass | S-Glass |
|---|---|---|
| $SiO_2$ | 52-56 | 60-65.5 |
| $Al_2O_3$ | 12-15 | 23-25 |
| $Fe_2O_3$ | 0.2-0.4 | 0 |
| CaO | 21-23 | 0 |
| MgO | 0.4-4.6 | 6-11 |
| $Na_2O$, $K_2O$ | 0-1 | 0.3 |
| $B_2O_3$ | 4-6 | 0 |
| | All in wt% (Nominal values) | |

**Table 3. 2: Composition of Glass used in fibre manufacturing** (178,179)

Glass is an abrasive material and during downstream operations (post-processing steps) and handling operations, fibres might rub against each other and this will introduce weak spots. To avoid this, the glass surface is coated with 'Sizing' which is a thin coating of aqueous emulsified polymer system. The benefits of 'Sizing' are as follows: protection against damage, facilitated handling, and improved adhesion between fibre and matrix. Key process steps in GF manufacturing is shown in Figure 3.5 are: Glass manufacturing, Sizing, Downstream Operations and Waste water treatment.

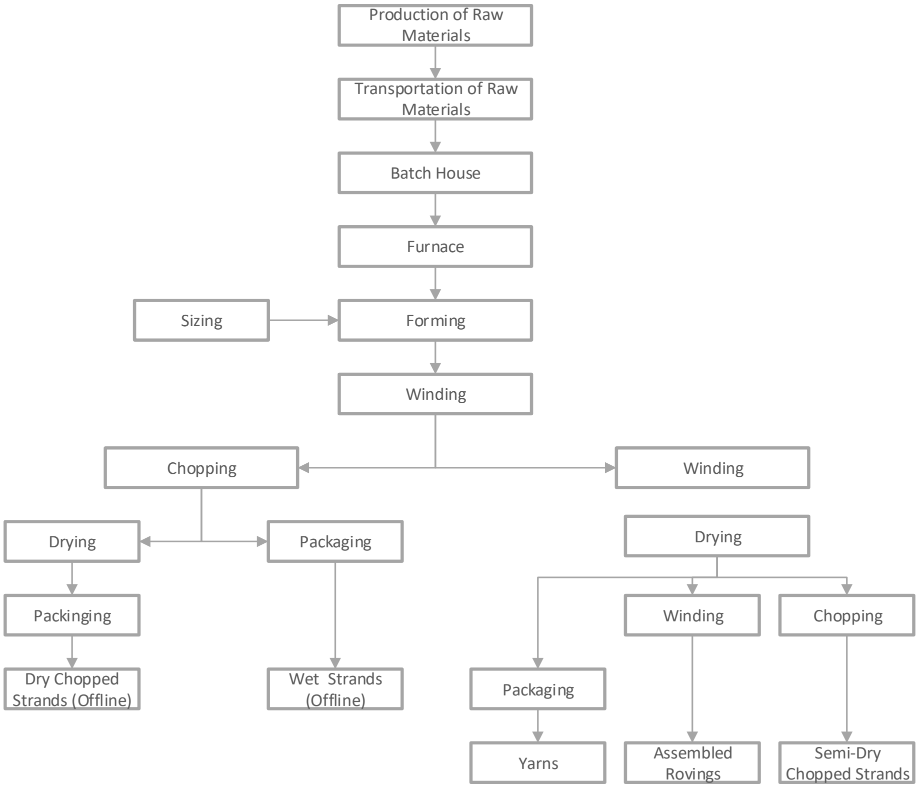


**Figure 3. 5: Glass fibre manufacturing process steps – extracted from Reference** (177).

Summary of cradle-to-gate inventory is summarized in Figure 3.6. Glass manufacturing by itself seems to be a major contribution to the total energy demand except for glass fibre mat in which mat manufacturing step shares up to ~40% of total energy demand.

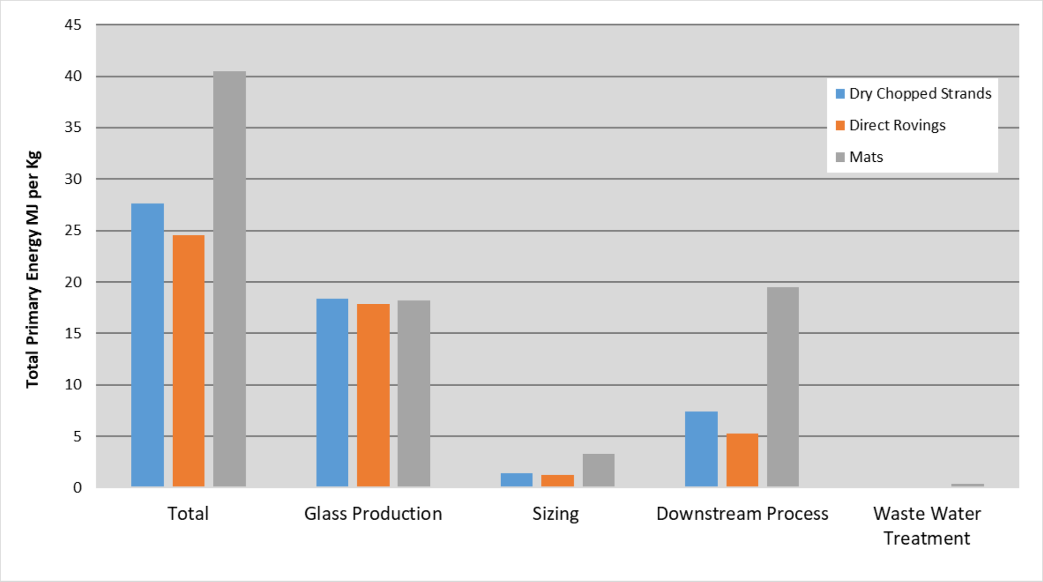


**Figure 3. 6: Primary energy consumption in GF manufacturing process – extracted from reference** (177)**. Showing energy consumption at various manufacturing steps**

## 3.4 Recycled Plastics

Polymer recycling operations involve a series of processes such as collection, sorting, shredding, cleaning, drying and extrusion pelletisation. For this study, recycled polypropylene is chosen as this is widely used in the retail industry and has numerous applications in domestic and industrial sectors. Recycling data is adapted from Vidal et al. (34). The waste collection truck is assumed to be a 7.5 t Euro 3 lorry. Recycling data is summarized as in table 3.3.

| Inputs | kg | Outputs | kg |
|---|---|---|---|
| Industrial waste | 1.3333 | Polypropylene | 1.0000 |
| Fresh water for washing | 0.1980 | Mud 65% Humidity | 0.3070 |
| Fresh water for extrusion | 0.3101 | Recirculated purified water for washing | 1.1280 |
| Recirculated purified water for washing | 1.1281 | Evaporated Water in Extruder | 0.3101 |
| NaOH | 0.0063 | Valorizable waste | 0.2552 |
| Anionic surface-active agents | 0.0013 | Valorizable metallic filter waste | 0.0001 |
| Zinc stearate | $3x10^{-5}$ | | |
| Lime (CaCO3) | 0.0017 | | |
| Flocculant (AlCl3) | 0.0016 | | |
| Electricity KWh | 0.0640 | | |
| Gas-Oil (KWh) | 0.0031 | 1% cut off applied on LCI | |

**Table 3. 3: Plastics recycling inventory data** (34)

## 3.5 Mechanical Performance

The mechanical properties of a composite are a critical factor in any composite applications, and it is one of a very basic material selection criteria for most of the applications from single use bags to aircraft components. In this study, Young's modulus and stiffness is considered as a key criterion as this is one of the most common material properties considered in applications including: semi-structural (91) and automotive (180) applications. Even though other properties such as strength, elongation, density, fatigue, creep, flammability, tribology and others are not reported in this study, this does not mean these properties are not critical for certain applications.

The Young's modulus of a polymer composite system is well studied by various authors in a large range of material systems including Epoxy-CF, PEEK-CF/GF, PP-GF, PP-NF, PP with nano fillers and fibres. In this study, with the help of various peer reviewed literature and micromechanical models (listed in Table 3.5), Young's modulus will be derived. The data used for this is shown in Table 3.4.

| Components | Longitudinal Elastic Modulus | References |
|---|---|---|
| Hackled Flax Fibre | Lower bound: 50 GPa | Vanden Oever et al., 2000 (181) |
| | Lower bound: 70 GPa | |
| Glass Fibre | 75 GPa | Vanden Oever et al., 2000 (181) |
| Recycled PP Matrix | Lower bound: 1.1 GPa | Albertsson et al., 2001 (182),<br>La Mantia, 2002 (183) |
| | Upper bound: 1.84 GPa | |
| Virgin PP Matrix | Upper bound: 1.84 GPa | Albertsson et al., 2001 (182) |

**Table 3. 4: Matrix and reinforcement properties**

The simplest micro-mechanical model equation is the Rule of Mixtures (ROM) represented as Equation 1. Eq.1 expresses that a given property of a composite is dependent on the volume fraction of the fibre and the matrix. This is based on the theory that when a stress is applied to the composite, the load acts on both fibre and matrix but the fibre bears the major part of the load (dependent on the volume fraction and mechanical properties) forming the basis of the reinforcement mechanism. Major disadvantages with this equation are disregarded for fibre matrix adhesion, length and orientation factors. It assumes that fibre and matrix have perfect adhesion with 100% stress transfer from matrix to the fibre which does not occur in real life.

Eq.2 is a modification of ROM by including an orientation factor which does not consider the effect of fibre lengths. Longer fibres provide maximum stress transfer leading to superior mechanical properties.

Halpin-Tsai Equations (H-S) are a set of empirical relations of fibre and matrix representing the composite system. The generalized form is shown in Eq. 4. The H-S model is an interpolation procedure (rather than extrapolation tool) to represent a complicated micro-mechanical system. The advantages of this procedure are simplicity and generalization of micro-mechanical results. The modulus values have good correlations with experimental values for various reinforcements such as fibres, flakes, and platelets. However, this model would not be useful for this study as it is not a predictive tool for extrapolation purposes (184,185).

Tsai - Pagano Model (Eq 6) was proposed to measure the properties of randomly oriented fibres from the Halpin-Tsai relation. Longitudinal and Transverse Elastic Modulus data from H-S would be used to obtain elastic modulus of composites containing random fibre orientation (186).

Manera (187) proposed a simplified equation (Eq 7) to predict properties of composites with random fibre orientation. This model is based on a classical laminate analogy, along with Tsai-Pagano functions and Puck's micro-mechanical models. Some researchers found that Manera's model seems to overestimate the elastic modulus (188).

Model (Eq 6) developed by Cox and Krenchal (181)(189)(190) is widely used to predict stiffness / modulus. The model contains orientation and length efficiency factors in a ROM equation. Stress transfer from matrix to reinforcement is controlled by length efficiency factor $\eta_L$ and the orientation factor, $\eta_o$, accounts for the effect of fibre orientation. The concept behind this equation is stress transfer from matrix to fibre via interfacial shear-stress gradually increasing from the fibre end to the middle which is shown in Eq 6b and 6c. Stress concentration at the fibre end is calculated through equation 6b through the shear modulus Gm, fibre length $\eta_L$ and geometrical packing factor $X_i$. In this study, a value of 4 is used for $X_i$ to resemble square packing factors and a value of 0.375 is used for $\eta_o$ to resemble random in-plane orientation. This model has been widely used and found to be valid in glass fibre and natural fibre reinforced materials (181,188,189).

The maximum volume fraction is limited to 25% as this will be equivalent to a weight fraction of 40-65% which is a typical maximum fibre loading in commercial thermoplastic composites. Virgin polypropylene and glass fibres are well established products and are expected to produce consistent properties between batches, hence only one modulus value is used. However, polymer waste feedstocks are expected to have some variation and this will affect the final polymer properties. Hence, lower bound and upper bound results are used. Flax fibre properties are reported with various modulus values in the literature and to accommodate these variations, moduli from two sources are applied in the model as lower bound and upper bound values.

| Eq. No. | Method / Model | Model Equation | Reference |
|---|---|---|---|
| 1 | Rule of Mixtures | $E_c = E_f + E_m(1-V_f)$ | Hull *et al.* |
| 2 | Rule of Mixtures with orientation factor | $P_c = \eta_o P_f V_f + P_m V_m$ | Gibson *et al* . |
| 3 | Halpin-Tsai | $\frac{p}{p_m} = \frac{1+\zeta\eta v_r}{1-\eta v_r} \quad \eta = \frac{(p_r/p_m)-1}{(p_r/p_m)+\zeta}$ | Jones *et al.* Mallick *et al.* |
| 4 | Tsai–Pagano | $E_c = \frac{3}{8}E_{11} + \frac{5}{8}E_{22}$ | Gibson *et al.* |
| 5 | Manera | $E_c = V_f\left[\frac{16}{45}E_{f1} + 2E_m\right] + \frac{8}{9}E_m$ | Manera *et al.* |
| 6(a),(b),(C) | Cox-Krenchal Model | $E_c = \eta_o \eta_L V_f E_f + E_m(1-V_f)$ - Eq 6a | Thomassan *et al.* |
|  |  | $\eta_L = 1 - \left[\frac{\tanh(\beta L/2)}{\beta L/2}\right] \beta = \frac{2}{d}\left[\frac{2G_m}{E_f \ln(\sqrt{\pi/X_i V_f})}\right]^{\frac{1}{2}}$ Eq - 6b & 6C | Oever et al. |
| $E_c$ = Elastic Moduli of Composite |  | $P_c$ = Property of Composite | $E_{11}$ = Elastic Modulus in Longitudinal Direction |
| $E_f$ = Elastic Moduli of Fiber |  | $P_f$ = Property of Fiber | $E_{22}$ = Elastic Modulus in Transverse Direction |
| $E_m$ = Elastic Moduli of Matrix |  | $P_m$ = Property of Matrix | $E_{F1}$ = Elastic Modulus of a Fiber in |
| $\eta_o$ = Orientation Factor |  | $V_f$ = Fiber Volume Fraction | Longidunal Direction |
| $\eta_L$ = Length Distribution Factor |  | $V_m$ = Matrix Volume Fraction | $E_{F2}$ = Elastic Modulus of a Fiber in |
| L = Fiber Length |  | $X_i$ = Geometrical Packing Factor | Transverse Direction |
| D = Fiber Diameter |  | β = Stress Concentration Coeffcient in Fiber Ends |  |
| $G_m$ = Shear Modulus |  |  |  |

**Table 3. 5: Composite micro-mechanical models. Reference numbers: Hull et al.** (168)**, Gibson et al.** (186)**, Jones et al.** (185)**, Mallick et al.** (184)**, Manera et al.** (187)**, Thomasan et al.** (189)**, Oever et al.** (181)**.**

## 3.6 Weight Reduction Calculation

A composition which gives a higher modulus produces a lighter panel. % weight reduction of the panel is calculated from component of derivations outlined by Ashby (191) for comparing different materials against steel to attain the same stiffness, and this methodology is used in automotive LCA's (192)(180).

$$M = \left\{\left[\frac{F}{\delta}\right]^{\frac{1}{3}}\right\} \left\{\left[CL^6B^2\right]^{\frac{1}{3}}\right\} \left\{\left[\frac{\rho}{E^{\frac{1}{3}}}\right]\right\} \qquad \text{Eq. 7}$$

As explained by Ashby (191) and Bhakshi et al. (192), Eq 7 has three parts indicated in parenthesis and explained in Table 3.6. With same stiffness, component geometry and deflection, the material with the highest material index is the lightest. Equivalent stiffness for different materials is assumed by increasing the component thickness (and component weight indirectly) rather than changing the geometry or introducing stiffness enhancing members such as I sections or ribs.

| Equation | Equation ID | Function |
|---|---|---|
| $\left\{\left[\frac{F}{\delta}\right]\right\}^{\frac{1}{3}}$ | Part 1 | Component Deflection |
| $\left\{\left[CL^6B^2\right]\right\}^{\frac{1}{3}}$ | Part 2 | Component Geometry |
| $\left\{\left[\frac{\rho}{E^{\frac{1}{3}}}\right]\right\}$ | Part 3 | Component Material / Ashby's Inverse Material Index |
| F - Force, $\delta$ - Elastic Deflection, L & B - Component Length and Width, C – Component Orientation Factor, | | |
| $\rho$ – Material Density, E – Material Elastic Modulus | | |

**Table 3. 6: Components of Ashby's equation**

Weight reduction will be calculated based on lifetime calculations of a mid-size car, weighing around 1492kg (192), consisting of multiple materials. Shannon et al.(180) assumed new materials were aimed to replace 7% closures and 19% body-in-white (BIW) (Body in white or BIW refers to the stage in automotive design or automobile manufacturing in which a car body's metallic components are joint together). In this study, scenario of 100% (all 7% in closures) of closures and only 2% (i.e 2% of 19% BIW which is 0.38%) of BIW which adds up to 7.38% of the total car weight or 110kg in total with metallic component is assumed to be replaced by recycled polymer composites. Ashby's material index (Part 3 in Table 3.6) is used to arrive at the degree of lightweighting and weight savings so as to keep component geometry and deflection same. % primary weight reduction estimation technique used by Shanon et al.(180) is adopted. Values used in the calculations are provided in Appendix 3A.

## 3.7 Fuel Reduction Value (FRV)

Fuel savings due to the weight reduction is calculated as per the method published by Koffler et al. (193). This has been widely adopted in peer-reviewed LCA studies publications (194–196). Fuel saving calculations are based on an internal combustion engine in a typical driving pattern defined as NEDC (New European Driving Cycle) as shown in Table 3.7 with lifetime mileage of 150,000 miles. NEDC is a combination of urban and motorway driving cycles to represent typical everyday usage of a passenger car. The weight-induced fuel consumption is calculated through mass induced energy demand, covering rolling resistance, aerodynamic resistance and acceleration resistance, including the degree of ICE engine efficiency. A summary of the calculation is as follows:

**Gasoline Engine: Approx. 0.15L per 100 km driving with 100 kg weight**

**Diesel Engine: Approx. 0.12L per 100 km driving with 100 kg weight**

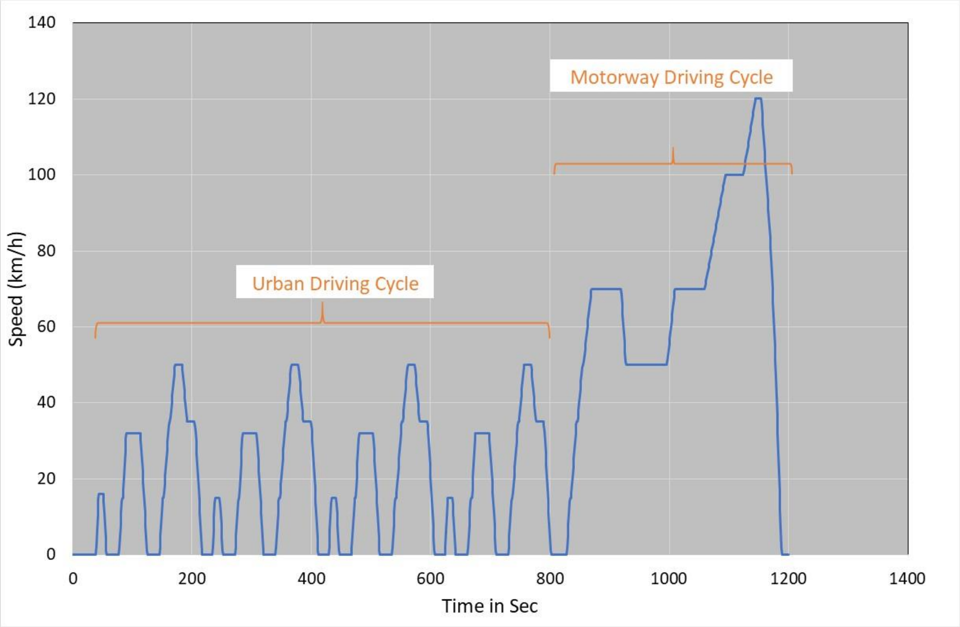


**Table 3. 7: New European driving cycle (NEDC)** (197)

In the FRV calculation, it is assumed that the vehicle's construction, such as gear ratio or engine displacements are not adjusted as the weight savings are not significant. A detailed explanation of these calculations could be found in the study published by Koffler et al. (193). A similar methodology has been adapted by other LCA studies (195,198) in material replacement applications. Values from FRV are used to estimate the fuel usage and use-phase impacts.

After the lifetime of the composite, products are assumed to be disposed of in a waste incinerator with energy recovery. Calorific values for different materials are obtained from the reported literatures and shown in Table 3.8. The energy obtained from incineration is considered to replace electricity and heat and it is valued as "avoided burden". The emissions from incineration are included from the Eco-invent LCI study but % moisture is adjusted from 15.9% to 1% to account for incineration of industrial waste rather than municipal waste as plastics waste considered in this study is more of an industrial nature rather than municipal waste.

| Material | Calorific Value (MJ/Kg) | Reference |
|---|---|---|
| Recycled / virgin PP | 48.9 | Roes et al., 2007 (199) |
| Flax Fibre | 20 | Duflou, 2014 (200) |
| Glass Fibre | 0 | Sain and Pervaiz, 2003 (201) |
| PP + Flax Fibre at 25% $V_f$ | 37.3 | Calculated from Above Data |
| PP + Glass Fibre at 25% $V_f$ | 17.1 | Calculated from Above Data |

**Table 3. 8: Calorific value data of the polymer and reinforcement system used in this study**

## 3.8 Life Cycle Impact Assessment

Life cycle impact assessment is carried out using the CML V.2.04 and Eco-indicator V 2.05 method through Simapro Software V 7.2.3 and a detailed calculation can be found in Guinee et al. (64) and the Eco-Indicator methodology (55). All major impact categories for composites at 25% $V_f$ are evaluated through CML method and are reported in Figure 3.7 and 3.8 and single score from Eco-Indicator methodology is reported in Figure 3.9. However, detailed analysis and discussion will be limited to Abiotic Resource Depletion Potential (ADP) and Global Warming Potential (GWP) as they are more relevant to recycling and resource recovery. The results from CML methods are reported after height normalization in percentages to facilitate comparison as measurement units between different impact categories are not the same. Raw data is reported in Appendix 2.

One of the objectives of this study is to evaluate the environmental impacts of these composites in two types of application: (I) civil and infrastructural, and (II) automotive applications. As already discussed in the previous section, fibre volume fraction plays a crucial role in obtaining the required mechanical properties and, for ease of comparison between different composites, environmental impacts will be reported in relation to mechanical properties rather than to fibre weight fraction where appropriate.

Abiotic Depletion Potential (ADP) = $\sum_i ADP_i \times m_i$

The $ADP_i$ is the abiotic depletion potential of resource i and $m_i$ is the quantity of resource used. The indicator is expressed in terms of kg of reference resource, antimony. The $ADP_i$ values of different materials can be obtained from Guinee *et al* (2001) (64). ADP signified resource usage.

Global Warming Potential (GWP) = $\sum i\ GWP_{a,i} \times mi$

$GWP_{a,i}$ is the global warming potential of substance i integrated over a number of years (a = 100 years in this case), while mi (kg) is the quantity of substance i emitted. $GWP_{a,i}$ values for different substances can be obtained from Guinee (2001) (64).

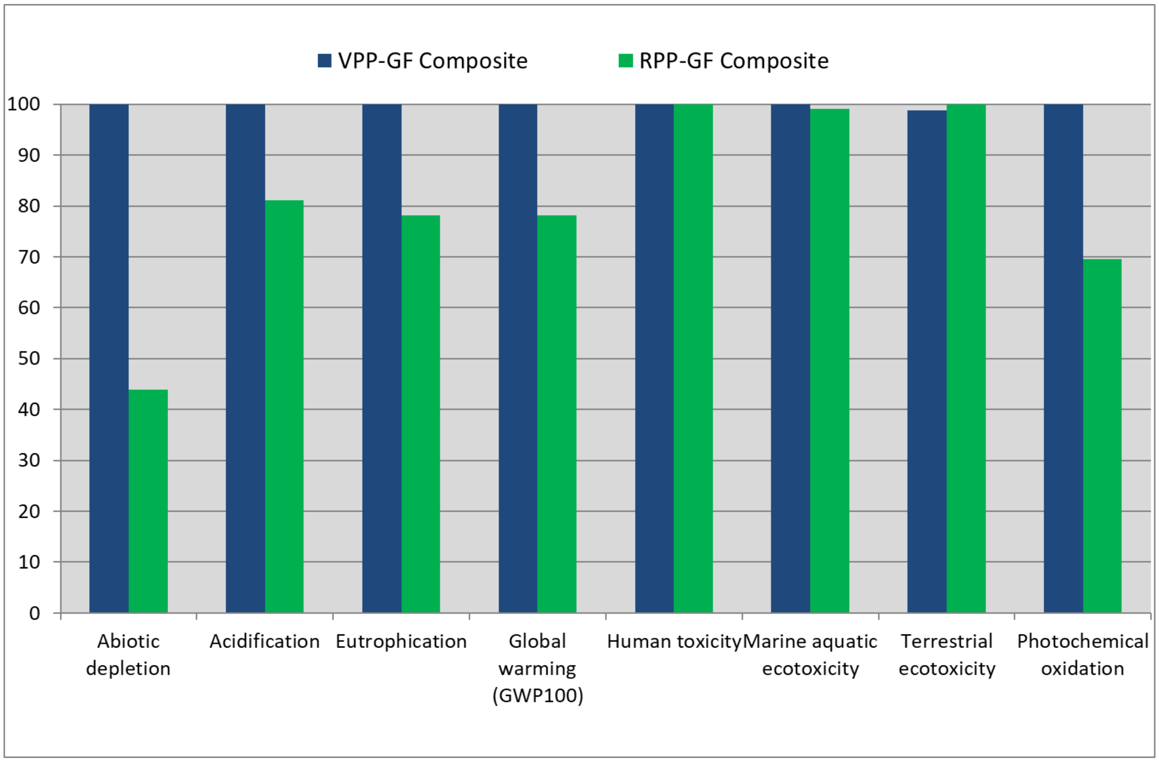


**Figure 3. 7: LCIA results through CML Methodology: VPP-GF and RPP-GF**

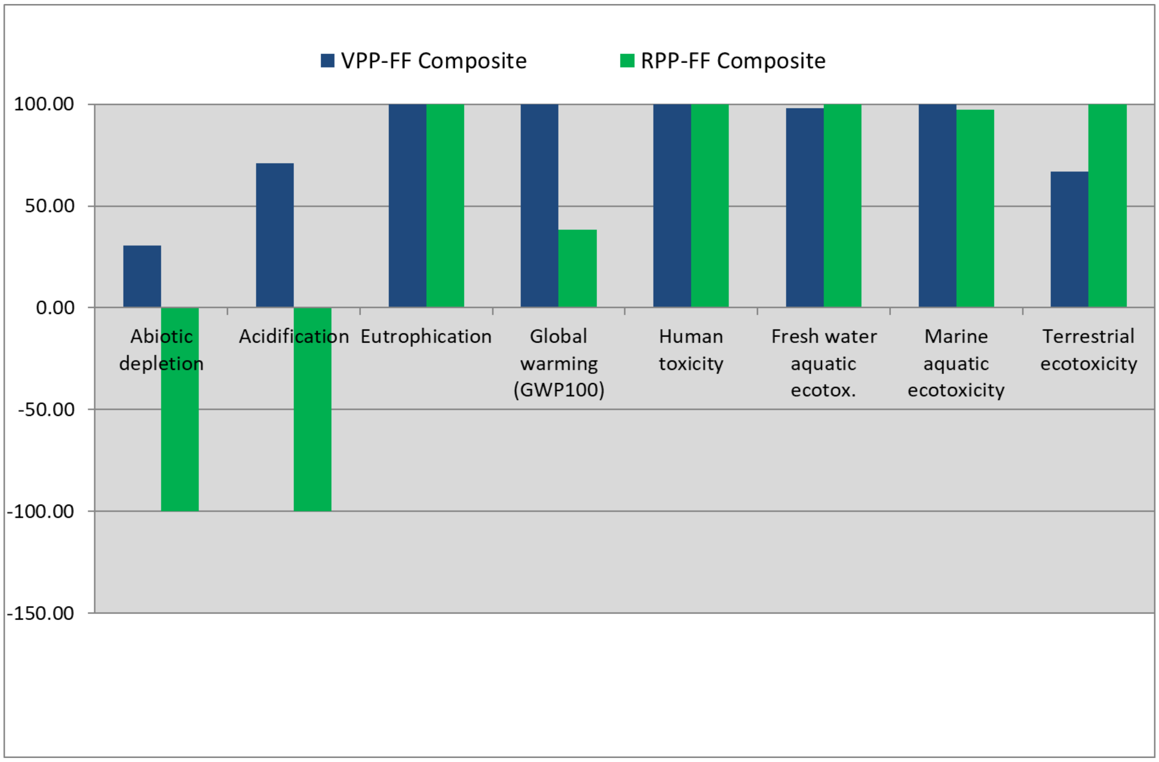


Figure 3. 8: LCIA results through CML Methodology: VPP-FF and RPP-FF

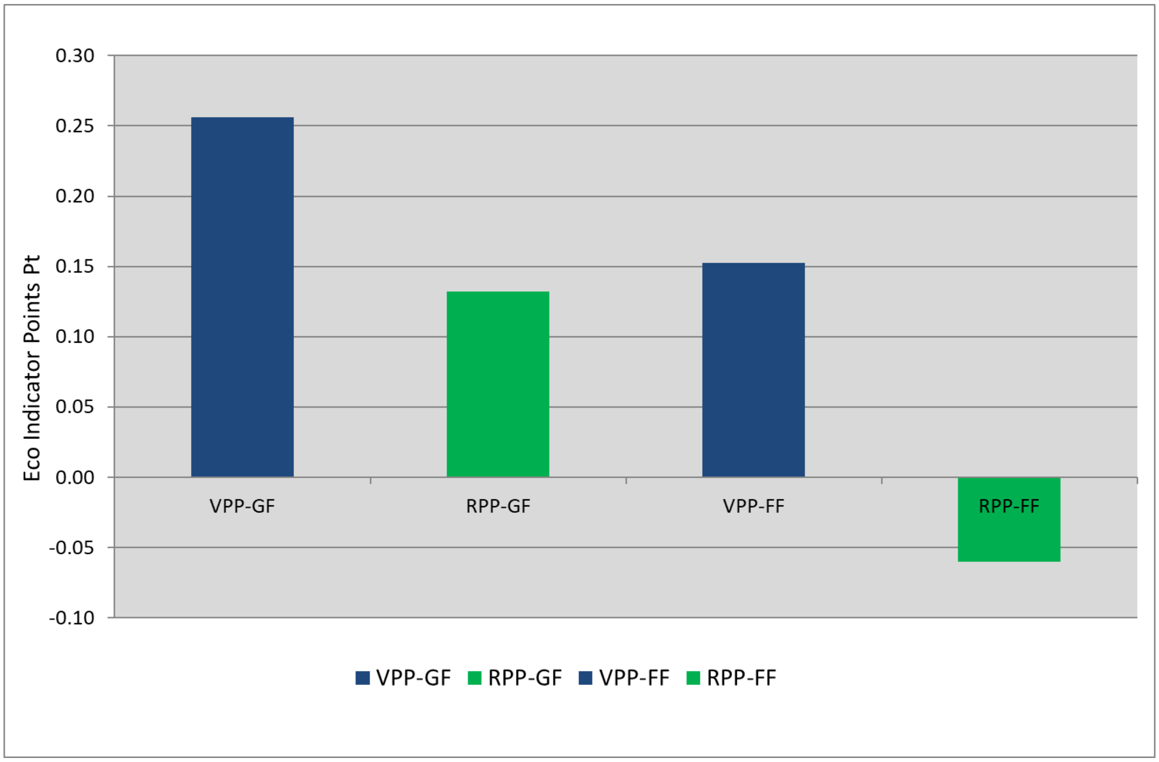


Figure 3. 9: LCIA Results through Eco-Indicator methodology: VPP-GFF, RPP-GF, VPP-FF & RPP-FF

### 3.8.1 Mechanical Properties of Composites

Elastic modulus calculated through the Cox-Krenchal model is shown below in Figure 3.10. The graphs show the effect of fibre fraction on the elastic modulus in recycled and virgin materials. As shown in the graphs, to address the variation in properties, lower-bound and upper-bound values are addressed for recycled PP and flax fibre.

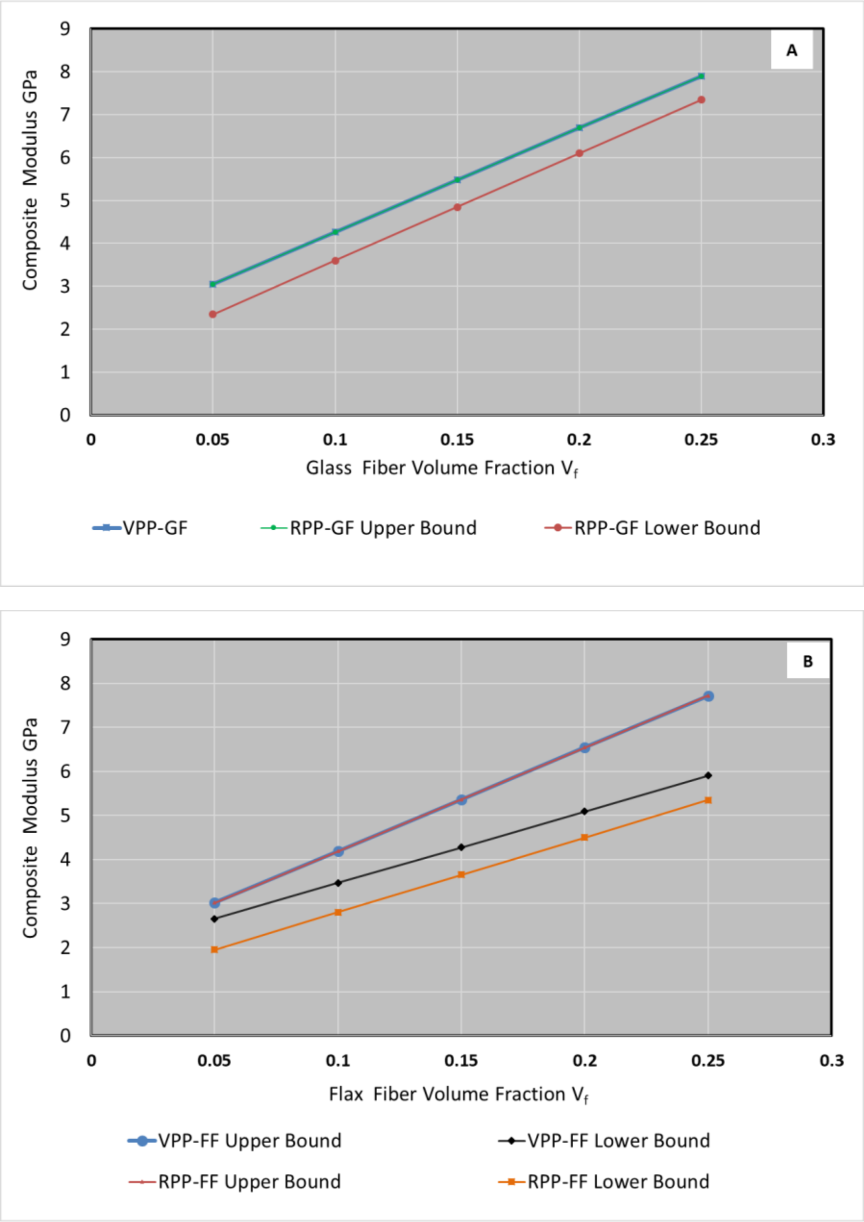


**Figure 3. 10: Effect of fibre volume fraction on mechanical properties of composites. A) Glass Fibre Composite B) Flax Fibre Composite. VPP-GF & RPP-GF upper bound in A and VPP-FF & RPP-FF upper bound in B overlay on each other**

### 3.8.2 Civil and Infrastructural Applications

The raw material manufacturing and end-of-life impacts are calculated based on inputs in the LCI section. The civil and infrastructural applications considered are applications like decking, fascia boards, moulded joists, footpath support, footpath planks, fence posts and similar products. Here use-phase impacts are minimal, apart from transport to the installation site and installation operation. Maintenance could fall within use-phase impacts; however, polymer materials are well proven to be low maintenance in these applications. This study is a comparative study of similar formulations, even if use-phase impacts exist, they will be similar and would not affect the outcome.

ADP and GWP are calculated and the correlation graph along with the mechanical properties are plotted in Figure 3.11 and 3.12. Data plotted in these graphs are inclusive of raw material and end-of-life impacts to represent civil and infrastructural applications.

### 3.8.3 Automotive Application

Polypropylene based composites are widely used in automotive applications (202,203). 68% of thermoplastic components in the Opel Astra model were made of polypropylene – for various internal and external components such as trims, door panels, body panels, battery cases and bumpers. In most of these applications, composite replaced metal. Steel is much stiffer than polypropylene composites and substitution results in increasing part thickness to achieve an equivalent mechanical performance. Increasing part thickness has a significant impact in automotive applications directly affecting use-phase impacts of an automotive component. As reported in automotive LCA studies, use-phase fuel consumption / fuel savings plays a significant role in offsetting environmental burdens that occur during manufacturing (195,204,205). Hence, fuel savings in both glass and flax fibre reinforced materials are evaluated as reported in reported in Figure 3.13 at its maximum $V_f$ of 25%. Whole life cycle GWP and ADP trend is reported in Figure 3.14 and 3.15 covering raw material, use-phase, and end-of-life. In automotive application analysis, the impacts of driving a car, its maintenance and road usage are ignored as these factors will not significantly influence the outcome as fuel usage dominates the use-phase impacts of automotive applications (refer to Appendix 3).

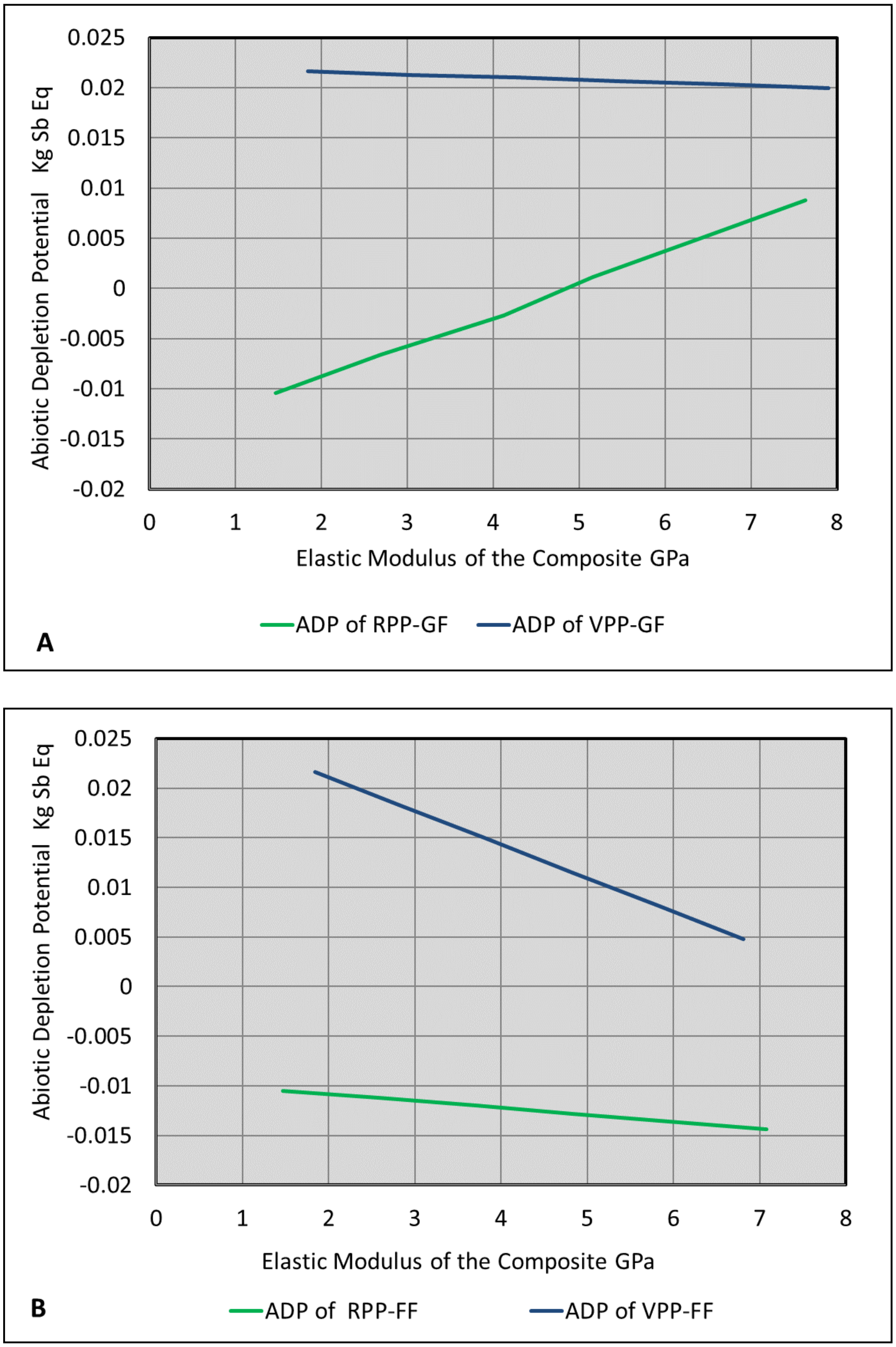
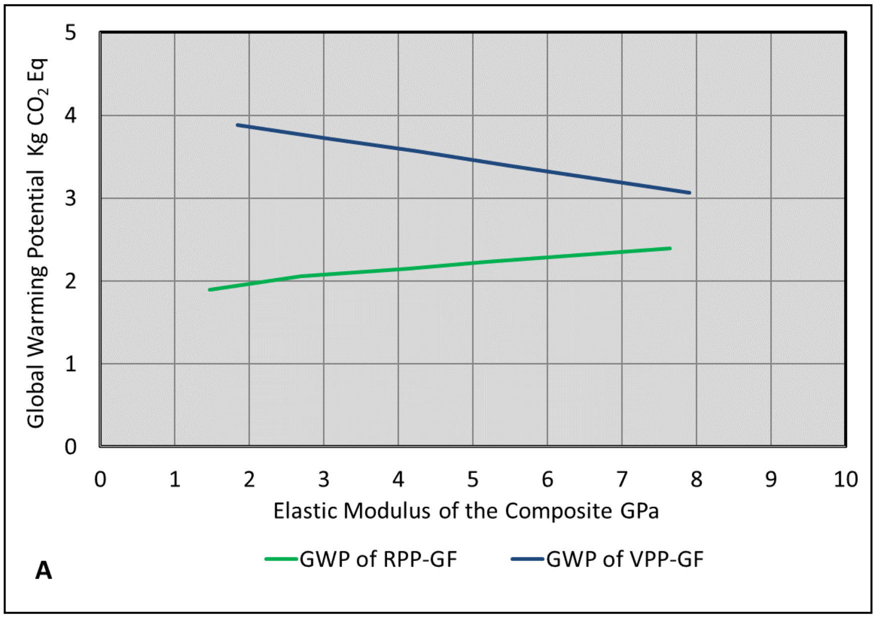


**Figure 3. 11: ADP and elastic modulus relation for glass fibre composite (A) and flax fibre composites (B) comparing the effect of recycled and virgin polymer-based composites. Data plotted in these graphs are inclusive of raw material and end-of-life impacts to represent civil and infrastructural applications**



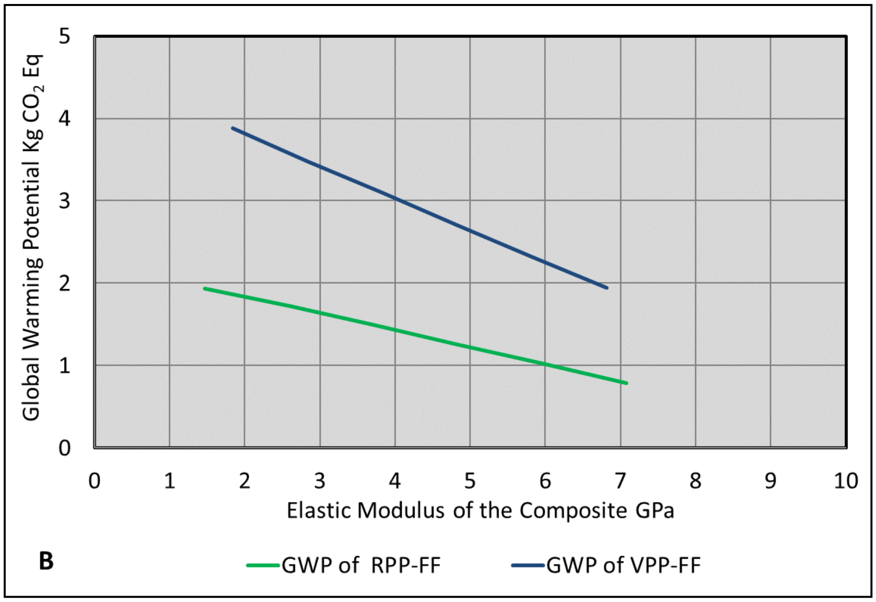


**Figure 3. 12: GWP and elastic modulus relation for glass fibre (A) and flax fibre composites (B) comparing the effect of recycled and virgin materials. Data plotted in these graphs are inclusive of raw material and end-of-life impacts to represent civil and infrastructural applications**

Composite processing steps are the same for both recycled and virgin materials, hence processing steps are not included in both cases as this is a comparative analysis. However, the effects of application in both the cases will be included in this case.

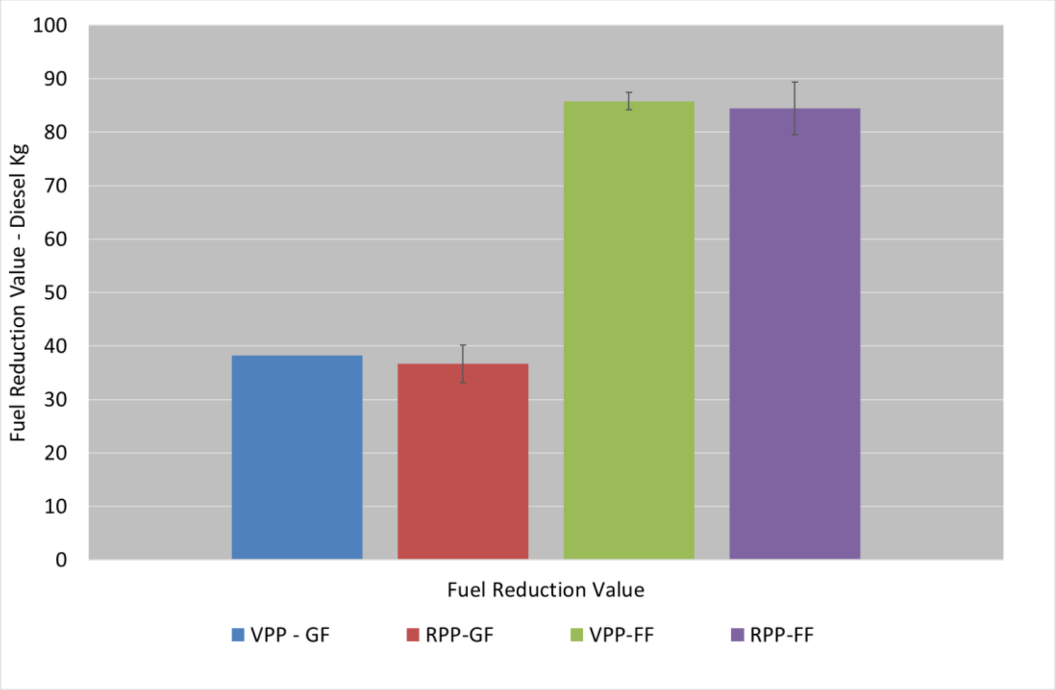


**Figure 3. 13: Fuel reduction values for automotive application for virgin and recycled products (Calculated based on NEDC driving cycle)**

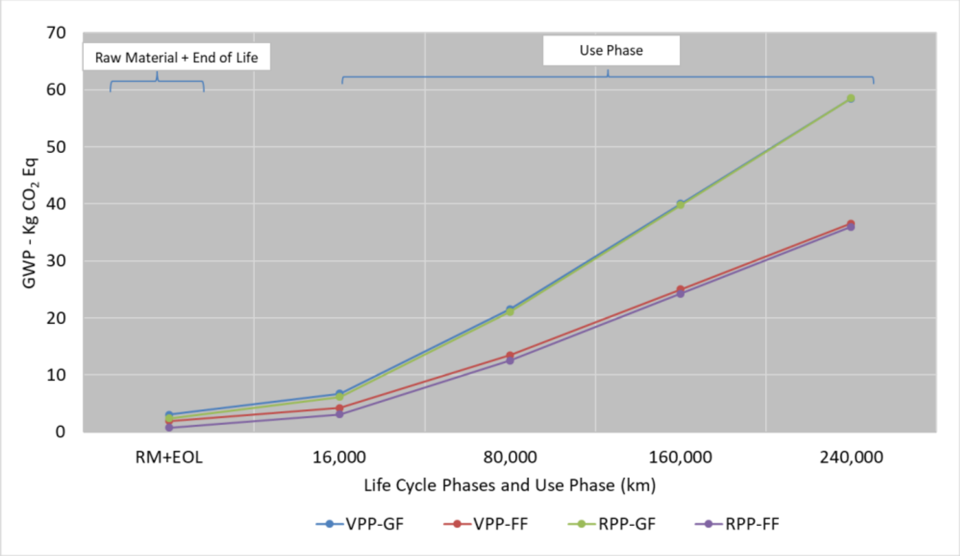


**Figure 3. 14: Automotive application life cycle showing GWP (VPP-GF overlaid on top of RPP-GF limiting the clear visibility of individual materials)**

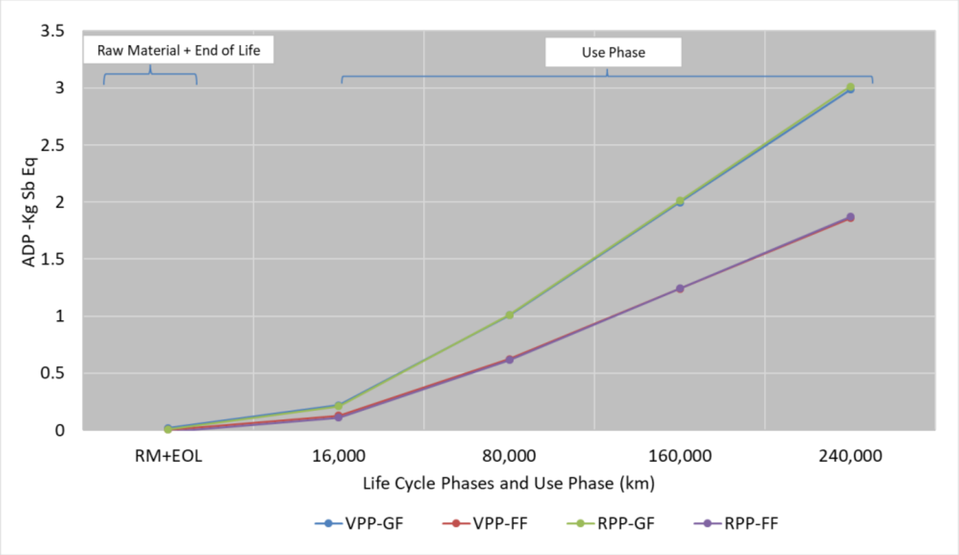


**Figure 3. 15: Automotive application life cycle showing ADP (VPP-GF overlaid on top of RPP-GF & VPP-FF overlaid on top of RPP-FF limiting the clear visibility of individual materials)**

## 3.9 Life Cycle Interpretation

The fundamental basis of this study is on enhancing mechanical properties of recycled PP with reinforcements. As shown in Figure 3.10, performance improvements are evident in recycled and virgin PP with GF and FF reinforcements. To account for inferior mechanical properties of recycled polymer, lower- and upper-bound results are evaluated and adapted in all the calculations. An attempt has been made to compare properties obtained in this study with experimental data for similar fibre-matrix systems. A comparison is shown in Figure 3.16 for the modulus. Properties were close at low fibre fraction; however, differences were around 50% at high fibre volume fraction. This could be due to sample preparation technique. Most of the reported studies including Thomassan et al. (189) used injection moulding to make the test samples. Injection moulding aligns fibres towards flow direction and provides significant improvements to tensile properties and this current study is based on random fibre orientation. To validate this theory, a random orientation factor of 0.375 has been adjusted to 50% random orientation and 50% unidirectional alignment (0.5 x 1 + 0.5 x0.375 = 0.6875) and properties are reported as orientation-adjusted properties which are very close to properties reported by Thomasson et al.(189) – within 10% variation at low $V_f$ content. Other differences such as fibre matrix adhesion, fibre length, and test conditions would have also influenced the properties. However, in this study both recycled and virgin PP composites are compared through the same micro-mechanical equations and hence error in prediction should not majorly affect the outcome of this study.

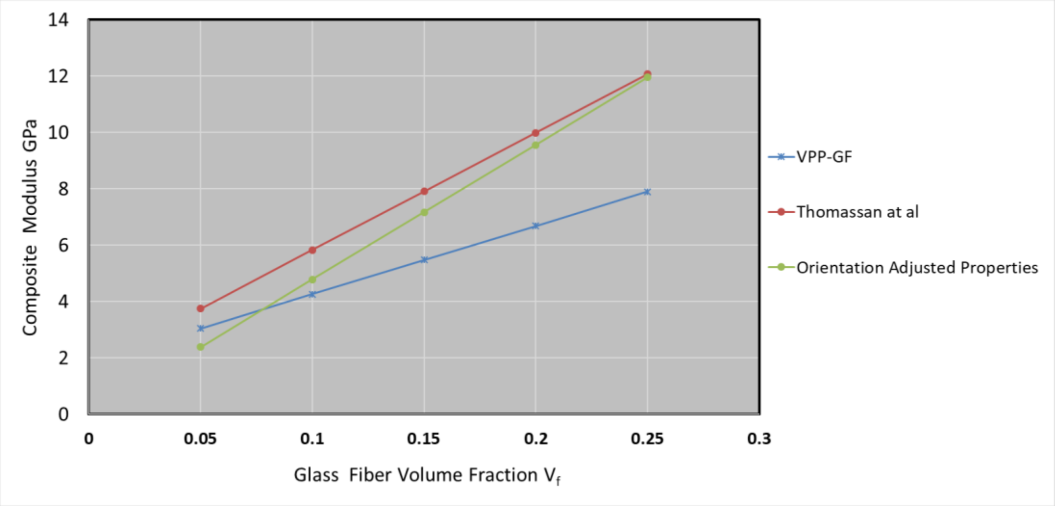


**Figure 3. 16: Composite modulus comparison: Cox-Krenchal prediction and experimental values**

LCIA results presented in Figures 3.7-3.9, clearly indicate that recycled polymer composites (RPP-GF and RPP-FF), at same fibre volume fraction $V_f$, have reduced environmental impacts compared with virgin polymer composites (VPP-GF and VPP-FF) in both individual impact categories (CML method) and combined impact categories (Eco-Indicator method).

Major impact categories such as resource usage, global warming potential and acidification impacts are significantly less for RPP-GF systems. Human toxicity potential is reported to be the same for both virgin (GF-VPP and FF-VPP) and recycled composites (GF-RPP and FF-RPP) and it is because of similar fibre volume fraction $V_f$ leading to a similar amount of matrix which gives off the same amount of emissions. Results from Eco-Indicator methodology clearly indicate that RPP-GF have 50% less emissions. At its maximum $V_f$, RPP-GF seem to have 5% poorer mechanical properties than virgin alternatives. Considering property reduction and environmental impacts, recycled polymer glass filled composites have clear and significant environmental benefits.

RPP-FF systems follow a similar trend to RPP-GF systems. However, quantified environmental benefits seem to be significant for RPP-FF compared with RPP-GF systems. This could be due to the dual influence from recycled matrix and bio-based fibres which are more ‘greener’ when compared with VPP-GF & RPP-GF materials. Another difference between GF and FF filled is incineration: flax fibre would burn and give energy during incineration but GF would not release energy. Most of the individual impact categories favour RPP-FF over VPP-FF. The combined Eco-Indicator single score shows that RPP-FF system has significantly less environmental impacts than any other glass fibre or flax fibre system. As flax fibres and the recycled matrix have the possibility of inferior properties, in figure 3.10, comparison between virgin upper-bound (VPP-FF) and recycled lower-bound (RPP-FF) results show a property difference of around 30%. Comparing average figures of VPP-FF and RPP-FF composites, the properties of RPP-FF composites are lower by around 5-10%. Considering both properties and the environmental advantage, RPP-FF seems to be a better product without considering the specific application with this material.

## 3.9.1 Applications

As mentioned in the scope, abiotic depletion and global warming potential will be discussed in detail for

- Civil and Infrastructural Applications
- Automotive Applications

### 3.9.1.1 Civil and Infrastructural Applications

Referring to results presented in Figure 3.11 and 3.12 – these are life cycle impacts of both raw material and end-of-life of VPP-GF, VPP-FF, RPP-GF, RPP-FF presented in relation to their mechanical properties. Since it is a comparative analysis, processing and use-phase impacts are not included and they are assumed to be the same for recycled and virgin systems. For any required modulus, recycled alternatives have environmental benefits. At any given modulus requirement in Figures 3.11-3.12, say at 5 GPa, the following observation could be found when comparing virgin composites against recycled composites ADP profiles.

- RPP-GF and FF composites have around 100% reduction in resource consumption
- RPP-GF and FF composites have around 40-60% reduction in global warming potential.

When modulus increases in GF composites, ADP potential seems to increase but an inverse relation is observed in the FF composite. This clearly shows that the recycled PP matrix and bio-based fibres are combined to achieve environmental benefits without losing mechanical performance.

In terms of GWP, both GF and FF systems follow similar trends as explained above. At any given modulus, RPP-FF has the lowest GWP, followed by RPP-GF, VPP-FF and finally VPP-GF composite.

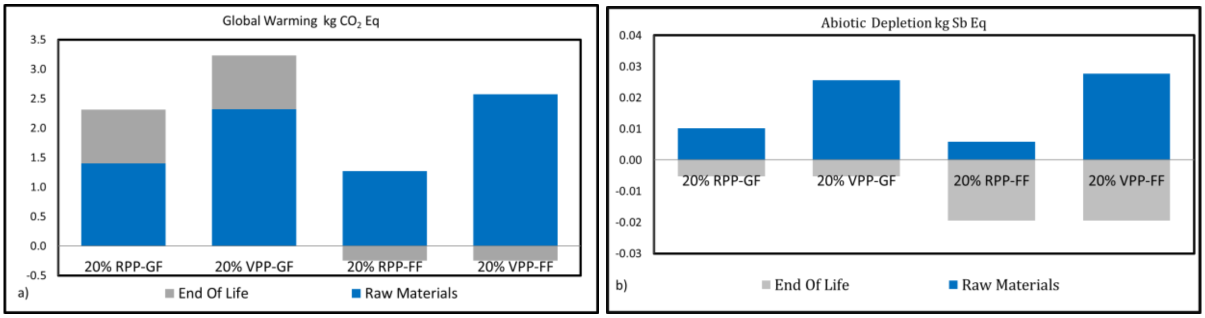


**Figure 3. 17: GWP & ADP Contribution analysis: non-automotive application**

The contribution analysis shown in Figure 3.17 adds insight to the numbers presented in Figures 3.11 & 3.12. In both virgin and recycled systems, in both GF and FF composites, EOL seems to create similar values because of avoided burden (of other fuels) generated through incineration of the composite. This increases the impact reduction potential of recycled materials. Following conclusions could be obtained from contribution analysis presented in Figure 3.17:

- Composites based on recycled polymers exhibit lower global warming potential and abiotic depletion potential in comparison with virgin alternatives.
- Energy generation potential of flax fibre provided a distinctive environmental benefit in both global warming and abiotic depletion. Incineration with energy recovery is expected to replace fossil fuels (used in energy generation process) which played a key role in magnifying the environmental benefit.
- EOL of flax fibre-based composites is better in getting lower global warming potential than glass fibre-based material owing to its energy generation potential. Calorific values are reported in Table 3.8 which indicates that FF based composites have more than 50% energy generation capacity than GF based composites.
- All EOL values in abiotic depletion potential are negative values with varying amplitude. However, only flax based material seems to have negative values in global warming potential. This indicates that recycling and use of bio-based fibres are efficient in reducing abiotic depletion potential than global warming.

### 3.9.1.2 Automotive Applications

As reported in automotive LCAs, use-phase outweighs impacts (206,207) generated in both raw material and EOL phases, particularly in lightweighting applications. Hence, this discussion will be predominantly around fuel consumption in use-phase. As shown in Figure 3.13, fuel reduction values calculated based on weight reduction seem to be very similar for both recycled (RPP-GF and RPP-FF) and virgin (VPP-GF and VPP-FF) materials. The fuel reduction value is higher for flax-based composites because of its specific stiffness. When comparing virgin (VPP-GF and VPP-FF) and recycled (RPP-GF and RPP-FF) materials, FRV is very similar and there is a possibility that FRV could be worse for recycled composites, as inferior properties demand heavier panels to meet the stiffness requirements. As shown in Figure 3.14 and 3.15, there is no clear crossover point between virgin and recycled materials and, at the same time, recycled products did not seem to significantly increase the impact. But if virgin PP with GF is going to be replaced by recycled PP with FF, then there will be a significant saving of around 100% in FRV, along with its associated tail pipe emissions and fuel upstream manufacturing.

## 3.10 Assumptions

This is a 'streamlined LCA' and it's important to understand the assumptions made in this study:

### Composite component manufacturing

It is assumed that the composite components in both virgin and recycled materials are manufactured in a similar manner and impacts are the same in both cases. In reality, this may not be the case. Recycled (or virgin) materials may require a longer moulding time which would increase manufacturing energy input.

### Composite properties

Lower-bound and upper-bound properties are applied in this study to account for variations affecting the end properties. However, composite interface is ignored in this study, as it assumes that both virgin and recycled materials have similar fibre-matrix adhesion. Recycled materials are a mixture of a different material grades and may not exhibit similar fibre-matrix adhesion.

### Material properties

Elastic Modulus is considered as a key criterion in this study. However, in both civil and automotive applications, several properties are critical, for example; fire retardancy, strength, elongation, machineability, paintability, aesthetics, chemical resistance, thermal expansion, and water absorption.

These properties should be considered when recycled materials are proposed for these high-value applications and where there is a possibility that some of these properties might limit use of recycled materials.

### LCA models and exclusions

This study is based on a hypothetical product, manufacturing facility and location, assuming travel between phases are uniform between recycled and virgin alternatives. However, there is a possibility that recycled or virgin materials could have different transport distances thus affecting the outcome of this study. This assumption is inclusive of energy mix as this study considers both products are manufactured in the UK. Wherever possible, models were kept very similar to each other to enable direct comparison to be made between virgin and recycled products.

## 3.11 Conclusion

This study utilized a 'streamlined' LCA technique to compare composite products made of recycled and virgin polymers. With the assumptions made in this study, it can be concluded that recycled composites could have a clear environmental advantage over conventional virgin plastics in certain cases. The advantages are evident in civil and infrastructural applications. The results from the automotive application analysis are not as clear. However, environmental benefits could be achieved if applications are analyzed on a case-by-case basis. Using recycled plastic in an automotive application will be environmentally favourable in the scenarios below:

- Components made of recycled plastic composites provide equal or higher FRV than that of its alternative
- Using flax fibre as reinforcement when replacing glass fibre filled composites.

The automotive industry has secondary, non-critical parts used in the cockpit and in other areas. Replacing them would be a straightforward choice as they are not a part of primary load-bearing structures. And owing to its market volume, large amounts of recycled plastics could be utilized. Building, construction and automotive applications together generate 30% of the 14 million tonnes of European plastic waste (165). Just a few applications in these sectors would make a significant difference in consumption of recycled plastics.

# Chapter 4: Estimation and Comparison of Environmental Impacts of Recycled Plastic Lumber with Softwood Lumber

## 5.1 Introduction

This chapter deals with the comparative life cycle assessment of recycled plastic lumber with the wooden lumber in construction sector. Recycled plastic lumbers are increasingly used to replace wooden lumbers in applications such as decking, boardwalks, staging, fencing and gates. Water resistance, rot resistance, frost impermeability, durability and low maintenance are considered to be prime selling points for recycled plastic lumber. This study deals with the comparative environmental impact assessment of plastic and wooden lumber to understand more about environmental implications through life cycle assessment methodology.

## 4.2 Prior Art

As reported in Chapter 1 & 2, hundreds of life cycle assessment studies have been published on polymer recycling and recycled polymer products. However, relatively few (less than 6 publications) of them are related to lumber-type products and relevant publications will be cited inn this section. One of the earlier studies on plastic lumber was conducted by Beck et al. (30) which recommended the use of the recycled plastic products in the marine environment as opposed to the toxicity of chromated copper arsenate (CCA) treated wood, as it was reported to be affecting the fertilisation of sea urchins. A carbon footprint study conducted on wooden and recycled plastic railway sleepers by Ana et al. (38) indicates that recycled plastic sleepers have potential $CO_2$ savings of up to 700kg per kilometre of railway track. Another study by Bolin et al. (159), comparing wood with wood composite lumber (WPC), claimed that wooden lumber is more sustainable than WPC lumber. The study included various unit processes such as tree growth, manufacturing, use phase and end-of-life, covering various process details. However, the end-of-life options were limited in this study, as it does not deal with disposal routes such as incineration or recycling.

Claiming a product as ‘environmentally sustainable’ is dependent on multiple direct and indirect factors. Therefore, in this study, an environmental impact assessment was carried out on a softwood lumber and a recycled plastic lumber with ‘incineration and energy recovery’ as end-of-life options.

## 4.2.2 Recycled Plastics Lumber

Recycled plastics lumbers were developed to replace wooden applications and have following advantages (101):

- Rot resistance with high life time up to 50 years
- Good dimensional stability and warp resistance
- Splinter resistance
- Non-toxic nature as it does not need toxic preservatives
- Recyclability
- Cost effectiveness
- Wood and wood texture look alike product
- Good machineability
- Low maintenance

Some of the common recycled plastic lumbers available in the market are (208):

- Recycled HDPE lumbers
- Comingled recycled plastic lumber
- Wood filled recycled plastic lumber
- Reinforced recycled plastic lumber. Glass fibre is one of the common reinforcements.

Reinforced plastic lumbers were mainly developed to improve the properties to make in comparable against wooden lumber. One of the novel products in recycled plastic lumber industry was the invention of structural recycled plastic lumber through optimizing the composition of plastic wastes to achieve significantly higher properties (102). Nosker et al. (92) achieved property improvement by utilizing rigid amorphous polymer (example polystyrene) to reinforce ductile materials (example polyethylene). Property improvements are in the range of around 100% in compression and flexural modulus (209). This composition was exploited and demonstrated by building a bridge (at Fort Leonard Wood, Missouri) with plastic lumber which is reported have load bearing of capability of 30 tons. Bridge consisted of 36 boards of structural grade plastic lumber (consisting of polystyrene) and 36 boards of standard lumber and weighing around 6 tons. 6 tons of plastic waste were mainly composed of HDPE milk bottles and polystyrene coffee cups which were diverted from landfill (94).

Reinforced recycled plastic lumber grades were reported to improve the properties tremendously as shown in Figure 4.1 (210) and makes the strength properties comparable to hardwood and softwood alternatives, but found to be still weaker in modulus indicating the susceptibility to high strain under loading conditions, particularly, creep loading conditions. Other fillers such as mica, talc, calcium carbonate, wood flour and cellulose fibers were attempted by researchers and reported to have improved the mechanical properties (211,212).

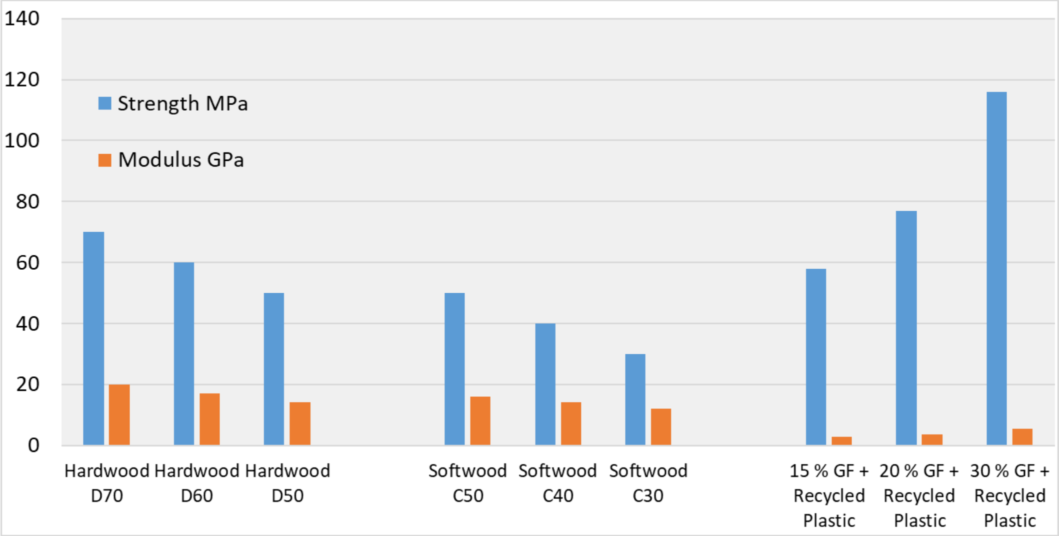


**Figure 4. 1: Strength and modulus comparison of wooden lumber and reinforced recycled plastic lumber** (210)**.**

## 4.3 Life cycle assessment (LCA)

The SimaPro Version 7.2.3 ((166)) LCA software package was used to compare treated wooden lumber and recycled plastic lumber. This LCA study exists between “streamlined” LCA and “full scale” LCA (78,155), i.e. the data used for the study are collected from different peer-reviewed literature sources. Where this is not available, they are estimated from semi-empirical models and from existing life cycle inventory databases.

### 4.3.1 Goal

The goal of this study is to quantify and compare the environmental burden associated with preservative-treated wooden lumber and recycled plastic lumber which is used in the United Kingdom with an end-of-life option as ‘incineration with energy recovery’.

## 4.3.2 Functional Unit

This study involves the comparison of $1m^3$ of preservative treated wooden lumber with recycled plastic lumber. The density of softwood lumber considered in the study is $480kg/m^3$ and the recycled plastic lumber is around $930kg/m^3$. Volume based comparison is adopted so as to keep the comparison simple. However, lower mechanical properties of recycled plastic lumber may need design modification when civil structure is built based on its mechanical performance (like bending strength). Design modification includes lower span, additional support, thicker and / or stiffer sections.

## 4.3.3 Scope

The system involves the manufacturing of lumbers, installation, use phase and end-of-life of lumbers. European Whitewood, European Redwood and Radiata Pine are softwood varieties which are used in the UK (213). This study includes life cycle modelling of a softwood plantation, growth, log yard activities, preservative treatment etc. for wooden lumber. It has been assumed that the manufacturing procedure and units process are the same for all three different wood varieties. The system boundaries are shown in figure 4.2.

Included in analysis:

- Wood (plantation, forest management, harvesting, sawmilling, transport from forest)
- Recycled polymers: recycling process and moulding
- Energy for production / manufacturing
- End of life: transportation to EOL site, EOL treatment (incineration)
- Life time comparison

Excluded from analysis: mainly because the activities are similar for both the materials

- Assembling the components
- Distribution activities
- Construction activities on site.

The LCI data, required for analysis, are from the eco-invent database, the Franklin database and other peer-reviewed literature as referenced. The transport distances assumed are:

- Plantation site to softwood lumber manufacturing site: 100 km
- Lumber manufacturing site to installation site: 100 km (for both cases)
- Installation site to EOL site: 100 km (for both cases)

In terms of impact assessment, the impacts are illustrated through single-score Eco-Indicator 99 methodology (endpoint) and also through CML methodology (64) (midpoint), with the following impact categories (midpoint) selected from the CML 2 baseline 2000 method:

- Global warming
- Acidification
- Eutrophication
- Photochemical oxidation (respiratory organics, summer smog)
- Human toxicity
- Fresh water aquatic eco-toxicity
- Terrestrial eco-toxicity
- Abiotic depletion

**Figure 4. 2: System Boundaries for comparison of softwood lumber and recycled plastic lumber**

The Eco-indicator 99 single-score is based on a methodology in which all impacts are summed according to their relative significance, and this is used in this study wherever the combination of impacts is necessary rather than an individual impact. More details can be obtained from Chapter 1 and Reference (68).

# 4..4 Life Cycle Inventory

## 4.4.1 LCI of Preservative Treated Wooden lumber

The product of primary focus is softwood lumber, Radiate Pine of 1m$^3$, which is grown widely in New Zealand and Australia. The LCI data is not readily available in any of the LCI databases. The inventory has been developed by assembling the individual components in Simapro. The references are carefully selected, ensuring that it is peer-viewed and they are cited appropriately allowing unit process traceability.

The softwood production activities from seedling to end-of-life have been modelled in Simapro V 7.2.3. The softwood growth and plantation activities involve the production of seedlings in nurseries, site preparation, slash burning, planting, chemical application of fertilisers, fire prevention & control, harvest and hauling of logs from forest to processing facilities. The LCI of softwood growth and plantation has been adopted from Jacqueline et al. (214) which covers the cradle-to-gate life cycle inventory of a softwood plantation in Australia. The inventory is shown in Table 4.1 (214). Sequestered carbon is estimated through dry weight, carbon content (50% of dry weight ) and Carbon-Carbon dioxide molar ratio 3.67 (215).

The softwood lumber production processes involve log yard activities, sawing, drying, and planing. The log yard activities such as unloading the logs from trucks, spraying water on the logs, and transporting the logs to sawmills were included. Debarking, chipping the portion of logs which did not make lumber, sorting according to sizes, and stacking green lumber for drying were included in the sawing unit process model. In kiln drying, the loading and unloading of lumbers, steam, electricity and fuel are included. The inventories are adopted from Wagner et al. (216). The softwood lumber manufacturing process data is shown in Table 4.2 (216). A weight-based allocation is followed in this process as all the co-products could be incinerated to obtain energy. The weights of wooden lumber at each stage are shown in Figure 4.3.

The wood preservation stage includes wood preservative manufacturing and treatment of lumber with wood preservative. There is a wide range of preservatives available for wood preservation. Wood treated with copper-azole-type preservatives are used in this study. The compositions of the preservatives are adopted from standards released by the American wood preservation association, P5-09 and P5-10 (217). The P5-09 standard insists that type A copper azole preservative should have a composition of 49% copper, 49% boric acid, 2% Tebuconazole; and type B should contain 98% copper and 2% Tebuconazole. Along with these basic components, ethanolamine is used as a carrier solution which is found to be around 3.8-4 times that of the copper content. The life cycle inventory for copper azole preservative is not directly available; hence they are modelled using existing unit process models from eco-invent. The life cycle inventory of Tebucanozole is also not reported in the literature and, as it is found to contribute to around 0.8 wt% of total preservative mix, they are neglected from this inventory. The quantity of preservative for treatment is predicted from the AWPA U1-11 standard (218) which specifies a copper azole retention of 0.1 pounds per cubic feet (1.6 kg/m$^3$) for above ground with exterior exposure use.

| **Natural resources** | Unit | Quantities |
|---|---|---|
| Land | hectare/m$^3$ | 0.11 |
| Water | ML/m$^3$ | 0.22 |
| **Energy** | | |
| Diesel | L/m$^3$ | 235 |
| Kerosene | L/m$^3$ | 0.06 |
| **Materials** | | |
| Lubricant | L/m$^3$ | 0.13 |
| Tyres | kg/m$^3$ | 0.07 |
| steel | kg/m$^3$ | 0.12 |
| gravel | kg/m$^3$ | 861 |
| Bitumen | kg/m$^3$ | 0.18 |
| **Fertilzer** | | |
| N | kg/m$^3$ | 0.56 |
| P | kg/m$^3$ | 0.37 |
| K | kg/m$^3$ | 0.11 |
| S | kg/m$^3$ | 0.44 |
| **Herbicide** | | |
| Below 2% not included in the inventory | | |
| Atrazine | g/m$^3$ | 11 |
| Glyphosate | g/m$^3$ | 6.9 |
| Simazine | g/m$^3$ | 5.7 |
| Hexazinone | g/m$^3$ | 4.2 |
| Triclopyr | g/m$^3$ | 0.4 |
| Other | g/m$^3$ | 1.2 |

**Table 4. 1: LCI of softwood growth and plantation. Extracted from Jacqueline et al.** (214)

| Process | Unit | Round wood conversion | Saw milling | Kiln Drying | Planing |
|---|---|---|---|---|---|
| Inputs | | | | | |
| Raw material | Kg | 836.07 | 778.54 | 476.31 | 436 |
| Allocation | % | 93 | 56 | 100 | 91 |
| Water | Kg | 34.05 | 0 | 0 | 0 |
| RFO | L | 0.07 | 0.08 | 0.08 | 0.1 |
| Diesel Equipment | L | 2.3 | 0.04 | 0.14 | 0.44 |
| Gasoline Equipment | L | 0.05 | 0.14 | 0 | 0.06 |
| Electricity | kwh | 3.12 | 20.77 | 18.26 | 34 |
| Wood in industrial boilers | kg | 0 | 0 | 60.48 | 0 |
| Natural Gas | $m^3$ | 0 | 0 | 28 | 0 |
| Outputs | | | | | |
| Emmmisions to Air | | | | | |
| Particulates | Kg | 0.15 | 0 | 0 | 0 |
| Hydrocarbons | Kg | 0.0004 | 0 | 0 | 0 |
| VOC | kg | 0 | 0 | 0.18 | 0 |
| Formaldehyde | Kg | 0 | 0 | 0.001 | 0 |
| Acetaldehyde | Kg | 0 | 0 | 0.002 | 0 |
| Methanol | kg | 0 | 0 | 0.025 | 0 |
| | | | | | |
| Final Waste Flows to Landfill | | | | | |
| (Below 2% not included in inventory | | | | | |
| Wood waste | kg | 9.99 | 0 | 0 | 0 |
| Wood waste | $m^3$ | 0.21 | 0 | 0 | 0 |

**Table 4. 2: LCI of softwood lumber manufacturing process data. Extracted from Wagner et al.** (216)

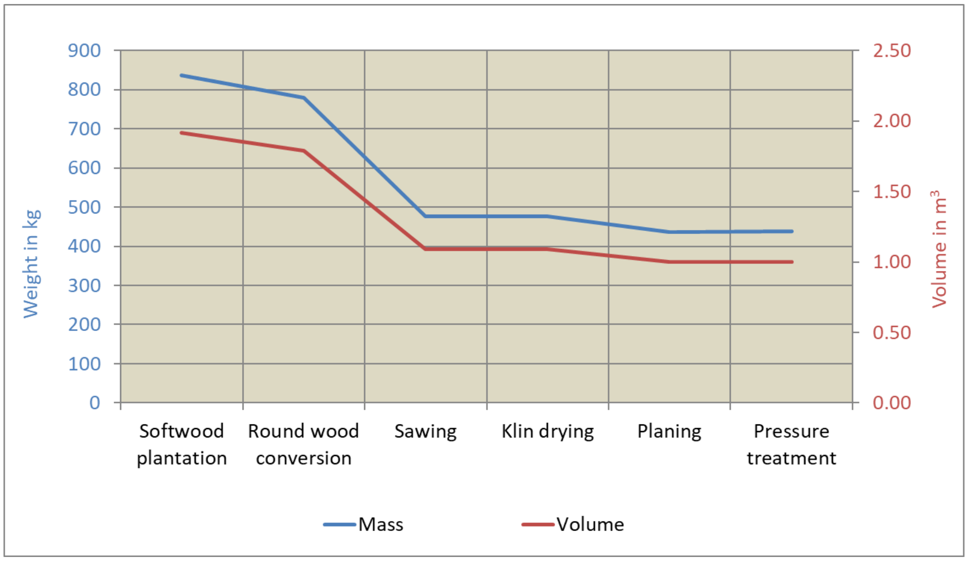


**Figure 4. 3: Lumber manufacturing stages showing yield trend** (216)

### 4.4.2 Plastic Lumber Manufacturing

As shown in Figure 4.4, the recycled plastic lumber in this study is composed of 100% recycled polymers, primarily polyolefins. The unit processes included in the study are shown in Figure 4.4. The process contained in the study includes shredding and granulation of plastic wastes followed by intrusion moulding to a lumber. Intrusion moulding is adopted particularly when the moulded product is of greater volume than maximum capacity of injection unit. The injection and extrusion processes are combined together to fill the product volume. The intrusion moulding machine used in the study is a 10-stage semi-automatic moulding machine. This means that 10 products are manufactured for a specific moulding cycle. The energy consumption data for the unit process are provided by one of the plastic recyclers. Confidentiality restricts reporting the raw data of lumber manufacturing.

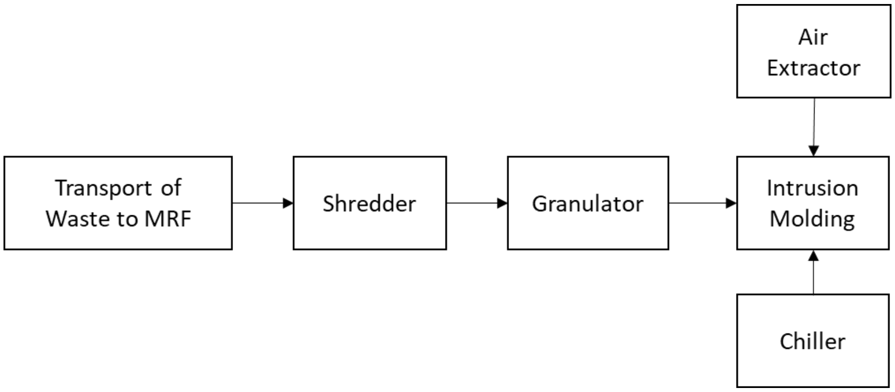


**Figure 4. 4: Recycled plastic lumber manufacturing process.**

### 4.4.3 Use phase

This phase involves inclusion of environmental impacts associated with the lumbers after installing in a specific application. This can be fence posts, agricultural woods in soil/manure content, poles, sleepers, pilings etc. This study is particularly focusing on outdoor applications such as when the product is in contact with the ground and water.

Preservative-treated wooden lumbers will last for number of years. The estimation of service life is debatable, as the life of treated softwood lumber varies according to service conditions. The LCA study conducted by Bolin et al. (159) used a life of 10 years, because lumbers are replaced for aesthetic reasons even though they are structurally capable of taking the load. In the case of recycled plastic lumber, the product durability is extremely high, and some manufacturers claim that the product can last for 50 years (38). In order to have a fair comparison, the impacts are evaluated with service lives of wooden lumber from 10 years to 20 years. This is introduced in the study as a life time ratio [LTR] which is calculated as shown below in equation 1. The LTR of “2, 1” indicates that the life of lumber is considered as 20, 10 years respectively. In the case of preservative-treated wooden lumber, there are studies available that researched the leaching of preservatives to the environment. However, due to the difficulty in accessing this literature which are in relation to LCA, the leaching behaviour is ignored in the current study.

Equation 4.1:

$$\text{Life Time Ratio [LTR]} = \frac{\text{Life of recycled plastic lumber (Years)}}{\text{Life of wooden lumber (Years)}}$$

### 4.4.4 End of Life

Incineration with energy recovery is adapted in this study as EOL. For incineration with energy recovery, an energy value of 14MJ per kg (20% Moisture) (219) is considered for wooden lumber and 48.9 MJ/kg (199) is assumed for recycled plastic lumber. Preservative-treated lumber is normally expected to release toxic pollutants from the process of incineration. However, references indicate that 99.9% of metallic compounds are left in the ash waste stream and the resulting emissions are similar to those of conventional fuels when burnt in modern facilities with an appropriate system and filters (40). Incineration in cement kilns indicates that the burning temperature is above 2000°C and additional purification features are not necessary as the temperature is sufficient enough to allow complete burn (220). The LCI is adopted from the eco-invent database (221), assuming that the wooden lumber is burnt in a municipal solid waste MSW incinerator with appropriate emission controls. Similarly, recycled plastic lumber is assumed to be burnt in the MSW incinerator and all environmental LCI data are adopted from eco-invent. The energy recovered from the incineration is costed as ‘avoided burden’, i.e. replacing electricity and heat. The electricity and heat data reported in Roes et al. (199) is adopted for this study. Heat and energy generation data used in this study is shown in Table 4.3.

| Calorific value of components | MJ/kg | Lumbers | MJ/m$^3$ |
|---|---|---|---|
| Wood with 0% moisture | 19.0000 | Softwood Lumber 1 m$^3$ | 6147.60 |
| Wood with 20% moisture | 14.1000 | Recycled Plastic Lumber 1 m$^3$ | 33480.78 |
| Recycled plastic with 0% Moisture | 45.0000 | | |
| Recycled plastic with 20% Moisture | 36.0008 | | |
| Water Calorific Value | 0.0042 | | |

| Energy Generation Capacity | Heat MJ | Electricity MJ |
|---|---|---|
| Softwood Lumber 1 m$^3$ | 737.7 | 737.7 |
| Recycled Plastic Lumber 1 m$^3$ | 4017.7 | 4017.7 |

| Energy Generation Capacity | Heat MJ/kg | Electricity MJ/kg |
|---|---|---|
| Softwood Lumber 1 m$^3$ | 1.7 | 1.7 |
| Recycled palstic Lumber 1 m$^3$ | 4.3 | 4.3 |

**Table 4. 3: Energy generation capacity derived from Roes et al.** (199)

## 4.5 Results: Life cycle impact assessment

The life cycle impact assessment is carried out using the CML methodology defined by Guinee et al. (2001) and Eco-Indicator 99 (55). The impacts are evaluated by multiplying the inventory with a characterisation factor and reported in Figures: 4.5 to 4.9 with both LTR 1 and 2 covering both CML and Eco-indicator methodologies. In order to understand more about the impacts, a contribution analysis was performed on wooden lumber (Figure 4.9). Owing to confidentiality, the contribution analysis of recycled plastic lumber cannot be revealed in this study. Since it is a comparative analysis, use-phase and the impacts from installation are ignored as they are assumed to be same. However, it has to be remembered that in the scenario of LTR 2 (in softwood lumber), installation impacts are twice that of the recycled plastic lumber. Some graphs show negative values which indicate environmental credits. It can be understood from the figures 4.5-4.9 that most of the impacts favour recycled plastic lumber. However, some of them favour softwood lumber. Reinforced plastic lumber is mainly discussed in scenario analysis. When quoted as recycled plastic lumber anywhere outside scenario analysis section (Section 4.7), indicates unreinforced recycled plastic lumber.

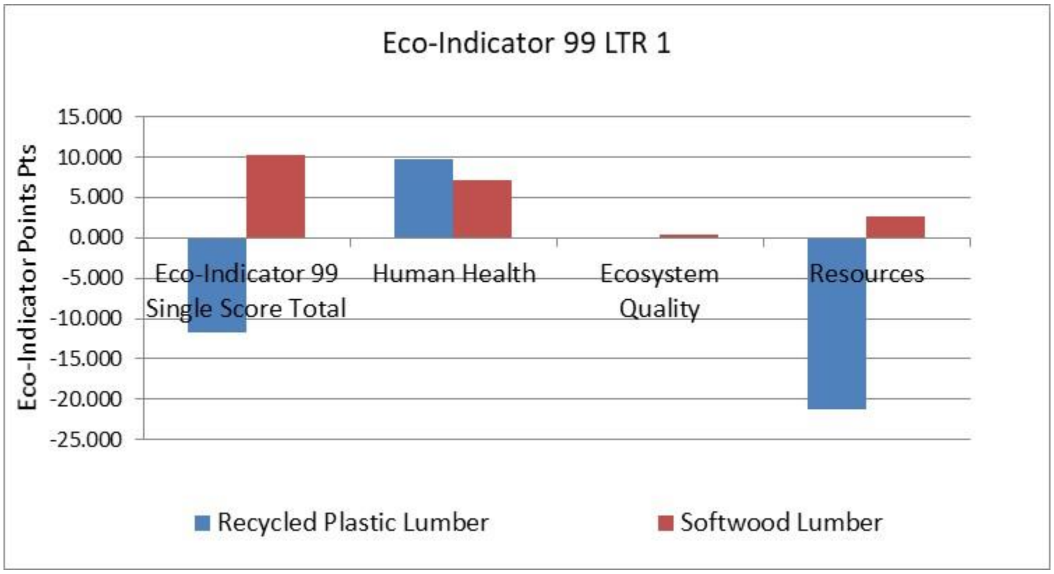


**Figure 4. 5: Eco-Indicator 99 Single score comparison between unreinforced recycled plastic and wooden lumber for LTR 1**

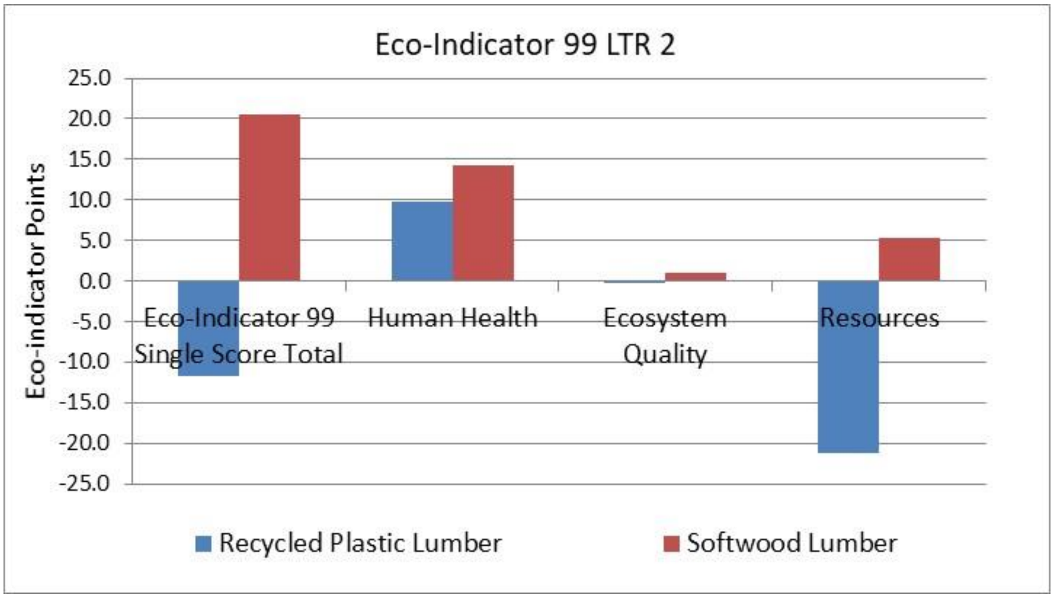


**Figure 4. 6: Eco-Indicator 99 Single score comparison between unreinforced recycled plastic and wooden lumber for LTR 2**

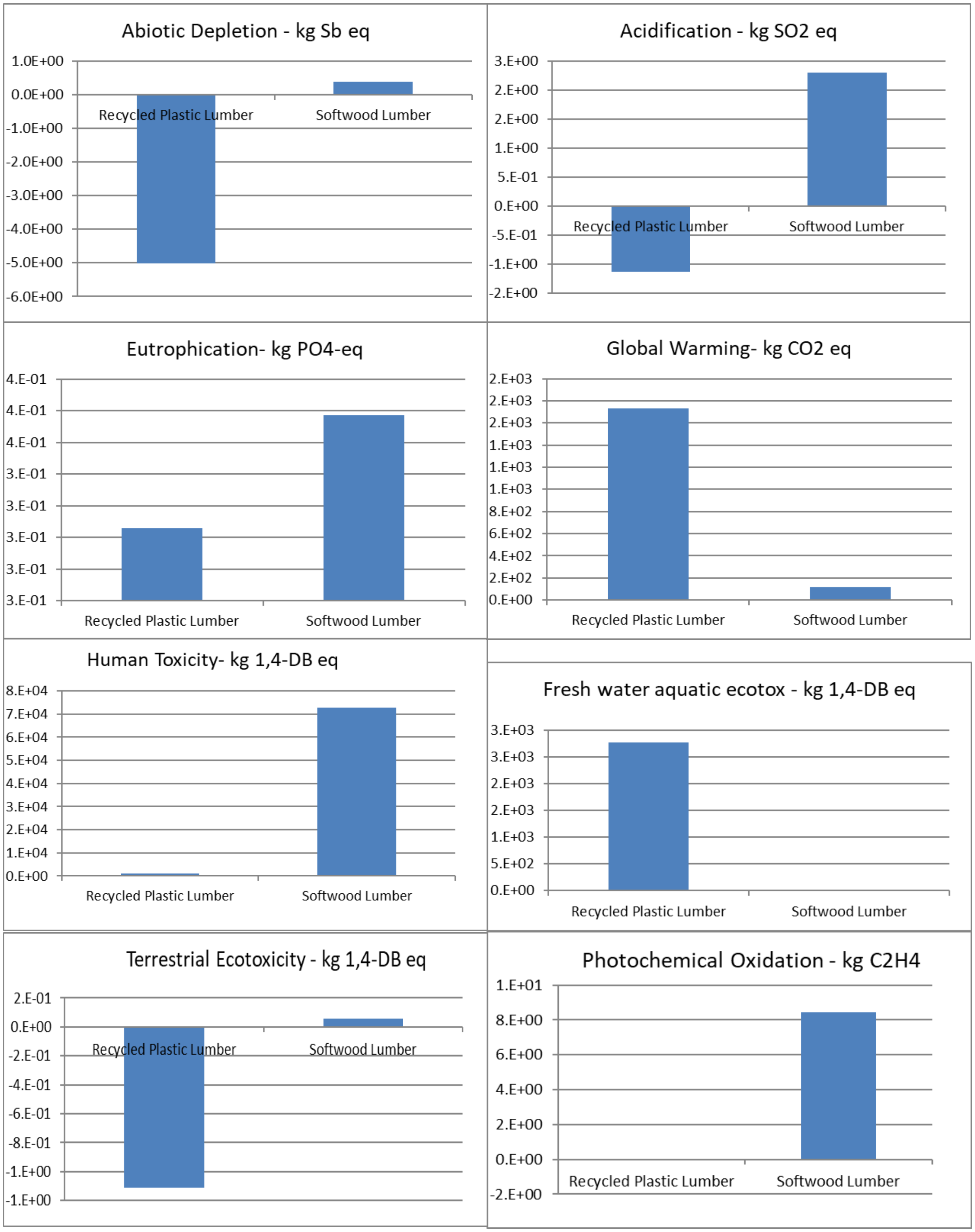


**Figure 4. 7: CML Methodology – Environmental Impacts for LTR 1**

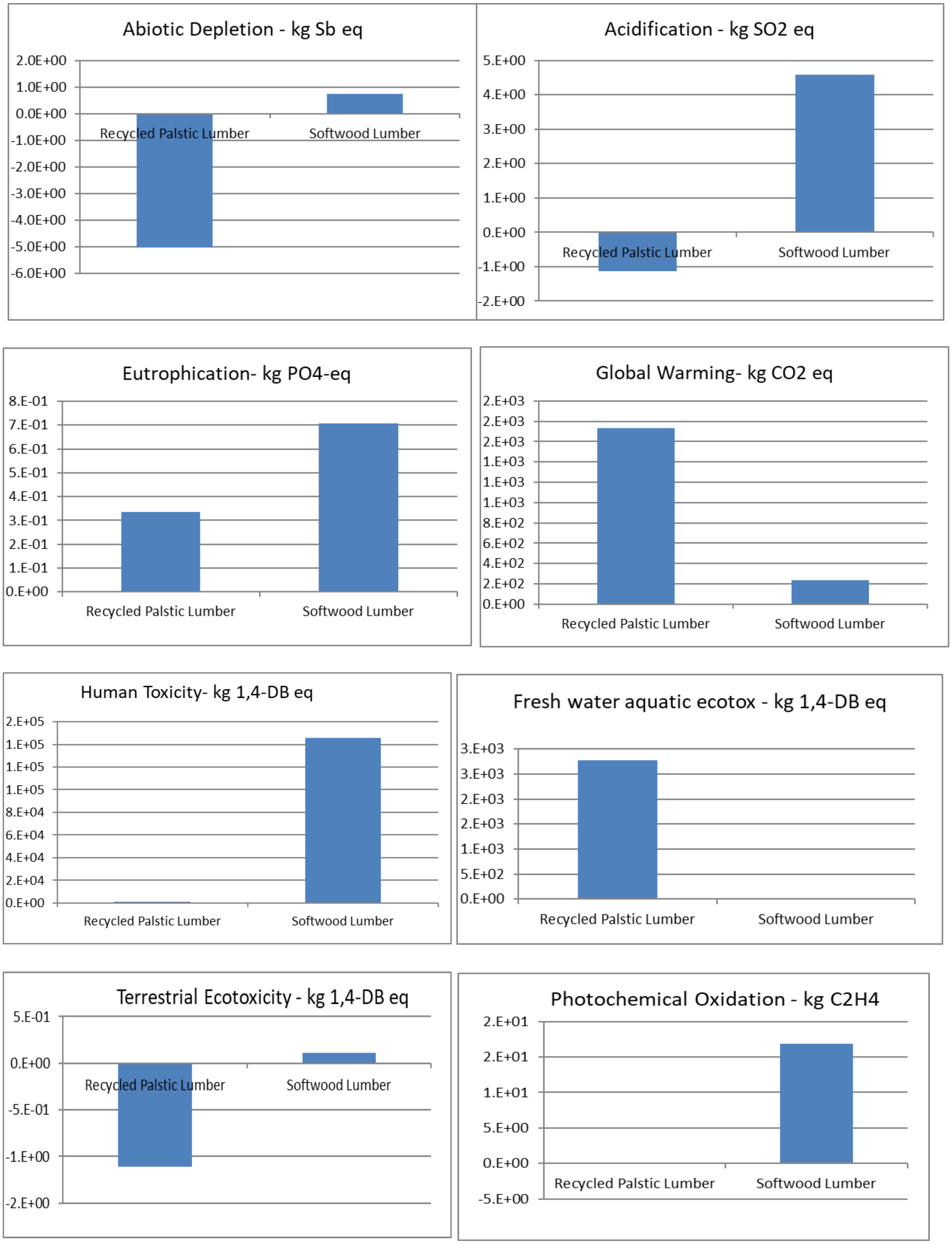


**Figure 4. 8: CML methodology – Environmental Impacts for LTR 2**

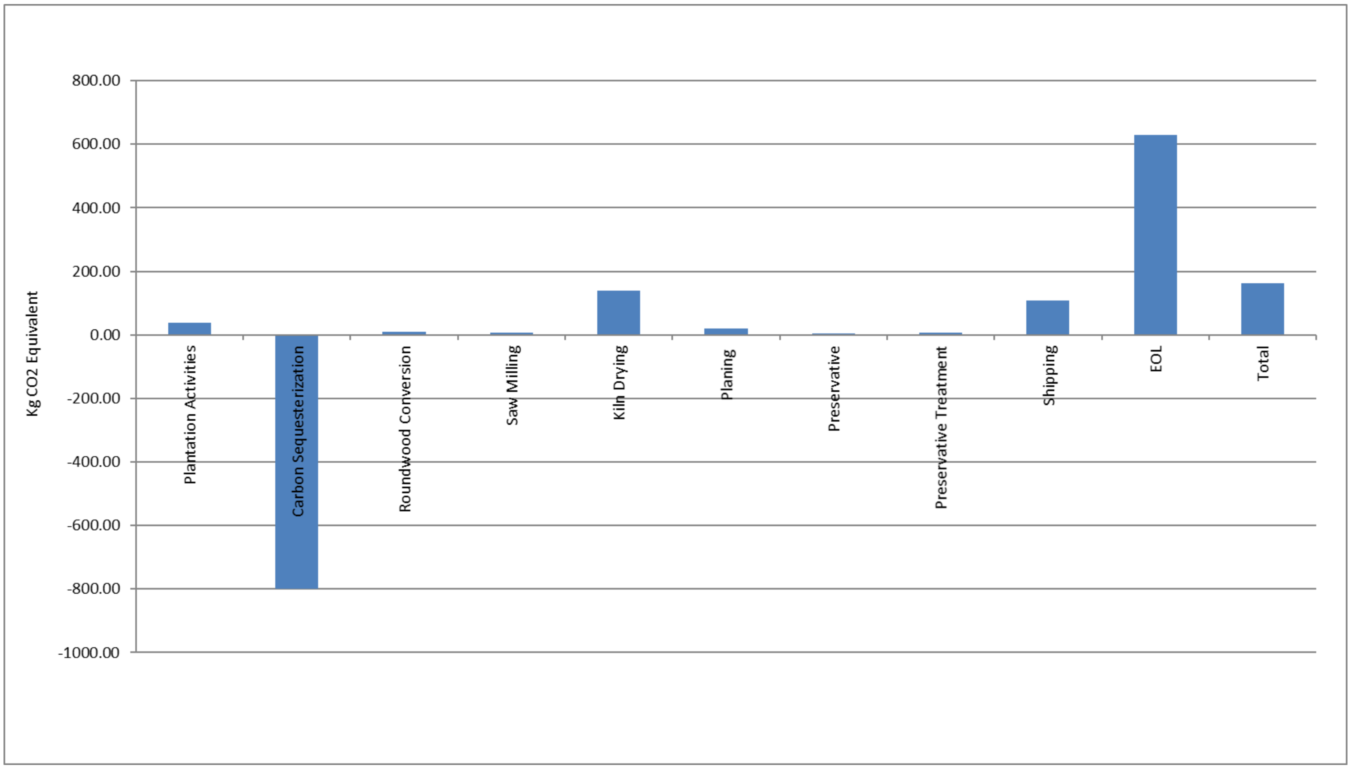


**Figure 4. 9: Contribution analysis of softwood lumber at LTR 1 represented in $CO_2$ emitted at various stages of softwood lumber manufacturing**

## 4.6 Discussion – Life Cycle Interpretation

The main difference in the life cycle impacts between softwood lumber and recycled plastic lumber are mainly due to their source. Wooden lumbers are sourced from forests which are well known for carbon sequesterisation. Conversely, recycled plastic lumbers are made from plastic wastes which are widely regarded as a “green” product. It can be clearly observed from Figure 4.7 and 4.8 that most impact categories favour recycled plastic lumber. However, the global warming impact is highly in favour of softwood lumber even under the consideration of less durability i.e LTR 2. It is evident from Fig 4.9 that carbon sequesterisation or ‘carbon neutrality‘ is one of the prime reasons behind this carbon credit.

The cradle-to-gate analysis was performed ignoring the carbon sequestration of trees. Results indicate that the global warming potential of recycled plastic lumber is still higher than the softwood lumber. The term ‘carbon neutrality’ of bio-products is subjective as it depends on factors such as the definition of carbon neutrality, the feedstock type, the technology used, and the timeframe examined. The WBSD (World Business Council for Sustainable Development) (222) believes that carbon neutrality is best understood as a condition wherein the net transfers of biogenic carbon to the atmosphere are zero (222). Photosynthesis converts solar energy from sun and $CO_2$ from the atmosphere into the chemical energy stored in trees, called biomass. When biomass is burned, or decays, the chemical energy is released and the $CO_2$ is placed back into the atmosphere, completing a natural carbon cycle. The carbon in biomass is "biogenic carbon" and the $CO_2$ formed when biomass is burned is "biogenic $CO_2$". The biogenic carbon cycle is in balance when the amount of $CO_2$ released to the atmosphere is brought back in to the earth as biomass. As long as the biomass carbon cycle is in balance, the release of biogenic $CO_2$ resulting from the use of biomass within that cycle does not cause atmospheric $CO_2$ to increase. In this study, we are assuming that products are manufactured from 'sustainably managed forests' and trees are planted in the forest after deforestation, and the softwood lumber is 'carbon neutral'. The carbon neutrality of softwood lumber effect could be observed in the global warming potential in Figure 4.9 and is the underlying reasons for lower $CO_2$ emissions.

Eutrophication, which is measured as kg PO4 equivalent, was found to be higher for softwood lumber than recycled plastic lumber. The contribution analysis indicates that the use of fertilisers is the main reason for an increase in eutrophication. Abiotic depletion, which is resource depletion, favours recycled plastic lumber with the main reason being that the amount of energy recovered from incineration is quite high and completely offsets the impacts generated by manufacturing the recycled plastic lumber. Plastics are high-energy materials and normally obtained from petroleum feedstock. The calorific values of plastics are almost equivalent to that of fuels and in the range of 30-48MJ/kg. The total heat and electricity generated by the incineration of plastics is ~40% higher than that of softwoods. Along with high energy content, the high density also favours the energy generation as the comparison is based on the fixed volume representing the market situation.

The acidification impact is represented as Kg $SO_2$ equivalent and was found to be higher for softwood lumber, whereas recycled plastic lumber shows negative emissions indicating the environmental credits. In the case of acidification emissions, more than 40% of the contributions were found be from energy usage for kiln drying of sawn wooden logs. The drying process is not included in recycled plastics lumber manufacturing as it is assumed that the waste plastics are sourced from industrial wastes. However, in case of domestic plastic waste, the washing and drying of plastic flakes might change the trend.

The cradle-to-gate comparison, without including EOL, indicates that the human toxicity potential of softwood lumber is higher than recycled plastic lumber. The contribution analysis indicates the ammonia, which is used for preservative manufacturing, is the major reason for increasing the human toxicity potential, particularly, the process emissions involved in the ammonia wet-steam-forming stage (166). The recycled plastic lumber does have a human toxicity potential with a value of 49.9 Kg 1,4-DB Eq which is mainly due to intrusion moulding, which in turn is due to energy consumption.

**Table 4. 4: Comparison of recycled plastics lumber studies**

| **Comparison** | **S Rajendran** | **Bolin et al** (159) |
|---|---|---|
| Lumber Manufacturing Inventory | Intrusion Moulding Data obtained from Industry | Unclear. Expected to have obtained from Arena et al. (27) |
| End of Life | Incineration and Energy Recovery | Landfilling |
| Preservative Leaching | Not included | Not included |

The single-score indicator is shown in Figure 4.5 & 4.6 which is the combination of all different impacts with appropriate weighting criteria. Comparison of softwood lumber and unreinforced recycled plastic lumber through eco-indicator methodology did not yield different results to the CML method. The eco-indicator score is significantly lower for unreinforced recycled plastic lumber when compared against softwood lumber. The majority of the impacts seem to be from resource depletion which, in turn, is because of energy usage in recycled plastic lumber and the human health impact from wooden lumber. As shown in Figure 4.10, the amount of energy generated from the incineration of plastics outweighs the process energy requirements of manufacturing recycled plastic lumber and makes the product “greener” when the products are compared with the eco-indicator methodology.

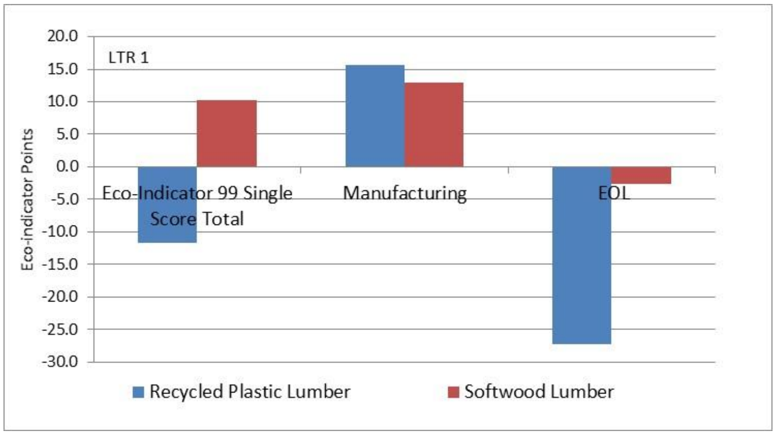


**Figure 4. 10: Eco-indicator 99 score showing process breakdown (LTR 1)**

Bolin et al. (159), compared softwood lumber with wood plastic composites; they favour wooden lumber in terms of most of the environmental indicators. The comparison (Table 4.4) indicates that the main difference is in the end-of-life options. Incineration with an energy recovery option is preferred owing to the limitations in landfilling.

## 4.7 Scenario analysis

Two different scenarios are analysed in this section as mentioned below:

- Effect of import of softwood lumber. i.e effect of shipping
- Effect of adding glass fibre as reinforcements.

The softwood lumbers are commonly used in the UK for a variety of applications. European whitewood, European redwood and Radiata pine are softwoods widely used in the UK. The Timber Trade Federation (TRADA) reported softwoods in UK includes both imported (outside EU) and home grown (within EU) (223). European whitewood and redwood are widely grown in central Europe, Norway, the UK, and Ireland (224). Radiata-Pine-type varieties are also grown in New Zealand. Hence the scenario was designed to see the effect of import on softwood i.e including the shipping impact from New Zealand. The shipping details were obtained from an expert (225): sea route via Panama canal, 11255 nautical miles travelling at 16 knots 19.2 days of travel from Wellington to Felixstowe. Data used in Simapro software in Transoceanic freight ship model containing eco-invent LCI data. The contribution analysis (Fig 4.11) was performed through eco-indicator to see the effect of shipping the raw material from New Zealand. The analysis indicates that around 40% of the total environmental impacts could increase because of shipping wood from countries like New Zealand. However, quantity imported from New

Zealand appears to be not major which makes this scenario less significant. The cradle-to-grave comparison was made between recycled plastic lumber, imported softwood lumber (with shipping), and softwood lumber from home grown forests and reported in Figure 4.12. Even though 40% of the impact increased, it was not significant enough to change the comparison outcome.

As reported in Figure 4.1, glass fibres and other reinforcements were reported to improve the mechanical properties. Hence, effect of glass fibre has been evaluated through Eco-indicator and reported in Figure 4.13. The data for glass fibre reinforced material was estimated from literature. Density of 1.080 g/cm$^3$ was used for used for GF filled recycled plastic lumber and data was obtained from industry data sheet (226). This indicates that 20% fibre filled polyolefin lumber will weigh around 1080 kg per m$^3$ volume. 20% w/w fiber will be equated to 216 kg of GF per m$^3$ of lumber which is used in LCI to estimate the effect of fibre reinforcement. Addition of GF analysed in this study seems to have significant effect in increasing the environmental impacts. Eco-indicator single score found have increased significantly. This increase is because of following reasons:

- Use of 20% GF: GF is a virgin raw material and GF manufacturing involves unit processes with significant energy consumption (177).
- GF is a high-density material. Density of GF is around 2.6 g/cm$^3$ whereas polyolefins are around 0.91-0.93 g/cm$^3$. Addition of GF will increase the weight of the product which will directly increase the use of more raw material.
- Addition of GF decreases the total combustible content in EOL phase and affecting the total energy recovery.

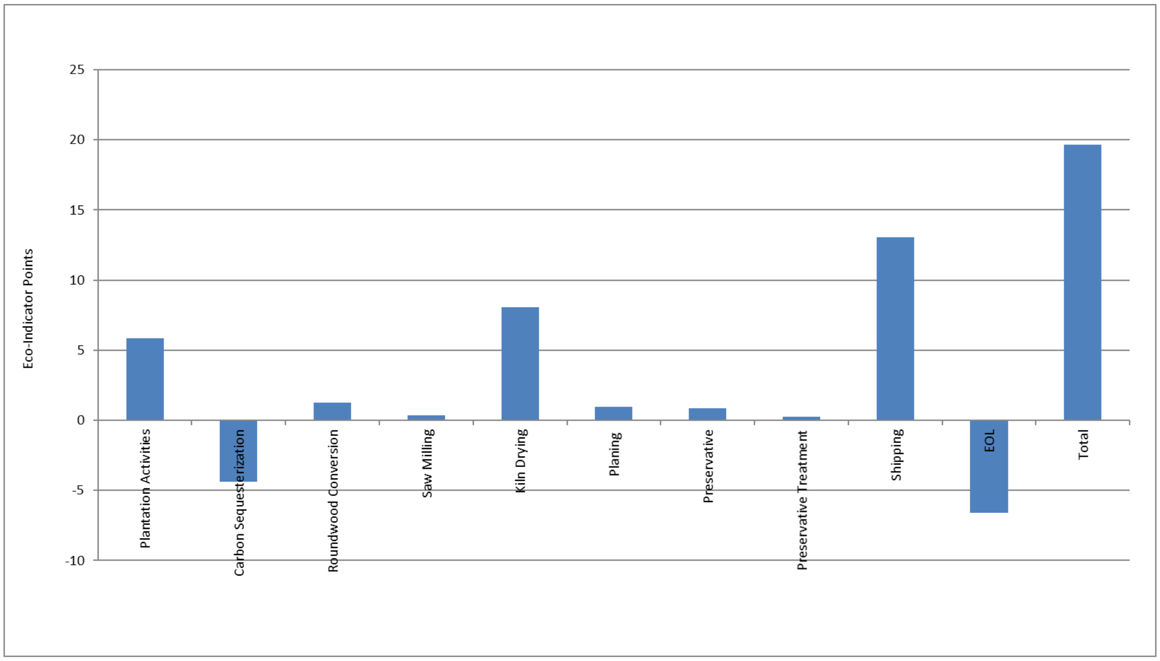


**Figure 4. 11: Contribution analysis showing the impact of shipping of softwood lumber from New Zealand (Unit: Single score Eco Indicator)**

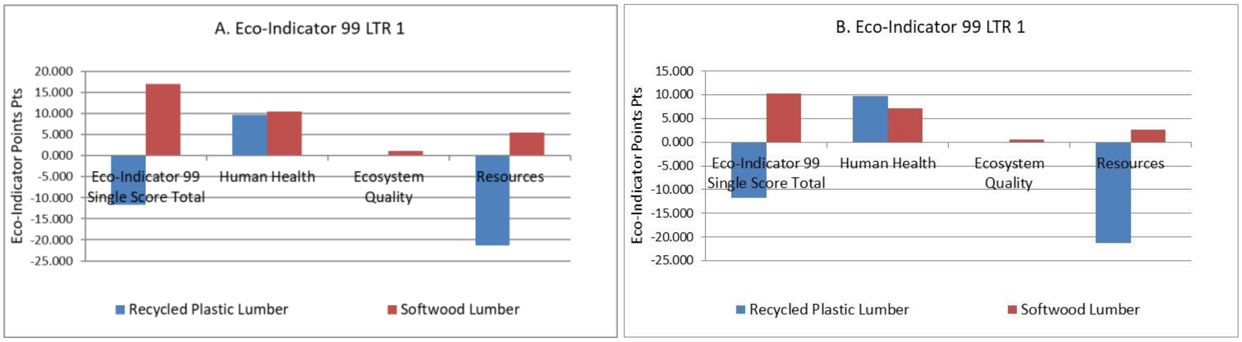


**Figure 4. 12: Eco-indicator 99 Results of LTR1 Scenario with Shipping (A) with homegrown Softwood (B) compared with unreinforced recycled lumber**

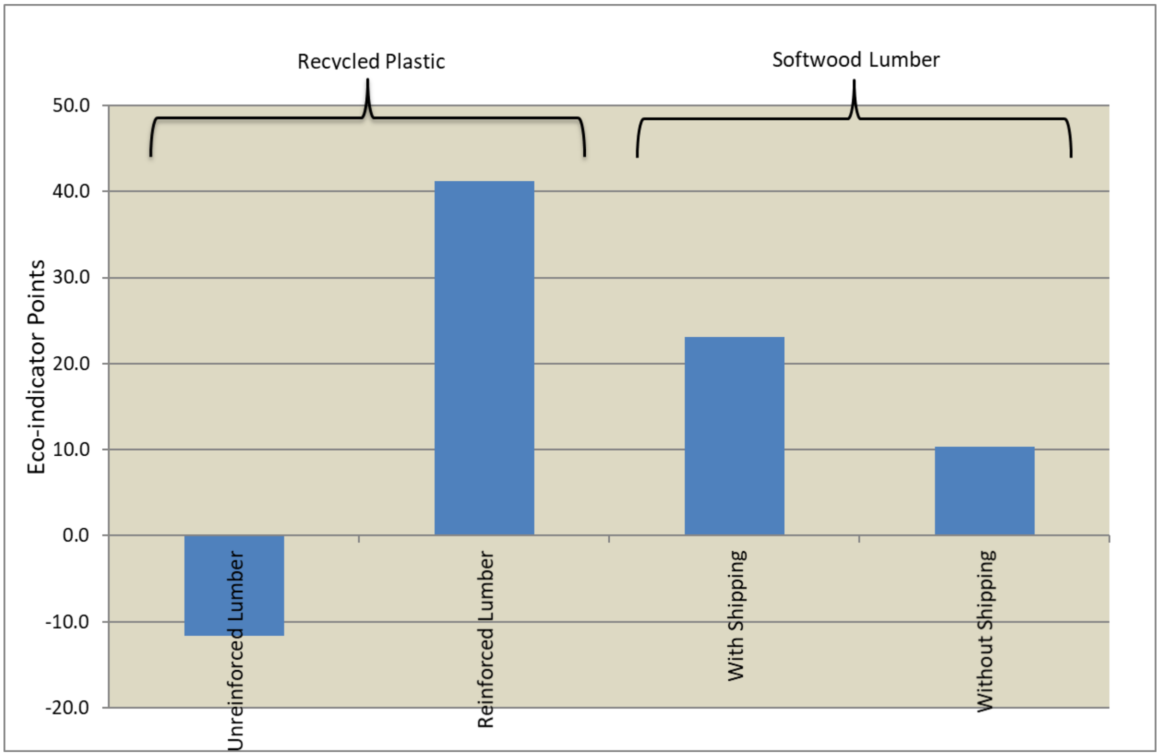


**Figure 4. 13: Scenario analysis evaluated through Eco-indicator 99 methodology - Environmental Impacts for LTR 1 showing the effect of shipping in softwood lumber and GF in recycled plastic lumber**

## 4.8 Assumptions

This study is applicable with the following assumptions:

- The raw materials for plastic lumbers are industrial waste which does not need any cleaning and drying processes. However, there are hundreds of plastic recycling companies which do clean and dry, particularly for domestic plastic waste recyclers.
- The wooden lumbers are chemically treated to enhance the durability and these chemicals have been reported to leach to the environment. Some references indicate that leaching of copper can be between 2-10% in an aquatic environment, and around 5% in soils. It has already been reported that the leaching of preservatives such as Copper azole, ACQ and CCA are reported to be toxic for aquatic organisms. However, this aquatic toxicity has not been included in this study (227).

## 4.9 Conclusion

Using the assumptions made in the study, it can be concluded that use of unreinforced recycled plastic lumber can have an environmental advantage over wooden lumber in some of the categories, however, not for all. The global warming potential, one of major environmental impacts, favours softwood lumber which is mainly because of the 'Carbon Neutrality' of forest products.

When environmental impacts indicators such as resource use, global warming, toxicity, eutrophication and acidification are summed through appropriate methodology (Eco-indicator 99), the results indicate that the unreinforced recycled plastic lumbers are environmentally a better candidate than softwood lumbers. Addition of reinforcements and importing lumbers found have significant effect in increasing the environmental impacts.

# Chapter 5: Plastics Recycling and Life Cycle Impact Assessment

## 5.1 Introduction

Environmental issues concerning plastics waste management are numerous and the effects are quite visible everywhere including land, forests and oceans. Indeed, the effects of such pollution are affecting most living beings including humans, animals, birds and sea life. Discarded plastics were found in forests, inland river streams, along the sea coast, the sea surface and sea beds (9,228). A recent report from the University of Rhode Island shocked the scientific community when scientists extracted microplastics from deep inside an ice block (229) at the Arctic which is supposed to be pristine clean and free from any pollution. This ubiquitous nature of plastic wastes led to a public outcry, and made local councils, polymer manufacturers, recyclers and institutions come-up with various measures to handle the waste in an effective way to minimise these environmental impacts. Materials like plastics, because of their chemistry and versatility, have diverse environmental aspects and life cycles and their end-of-life could be very complex to manage as shown in Figure 5.1.

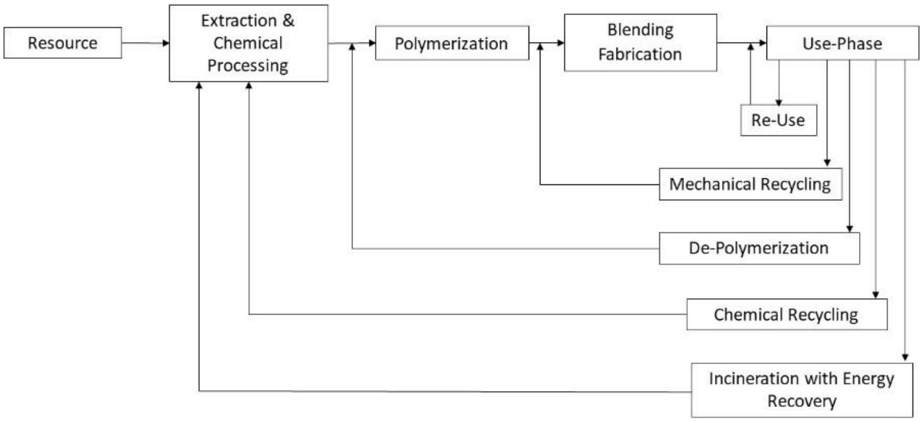


**Figure 5. 1: Polymer life cycle with various end-of-life choices** (82)

On the other hand, plastic waste, by itself is a renewable source to obtain various materials, chemicals and energy. García et al. (230) reported that one ton of plastic waste is equivalent to 130 million kJ of energy (the same as that normally obtained through combustion of 22 barrels of oil) indicating two sides of plastic wastes could be looked: a source of renewable material on one side, and a source of serious pollution on the other.

The chemistry of polymers allows products to be re-used or mechanically recycled to repelletize or chemically depolymerize to make monomers / chemicals or incinerate to recover energy. These various

End-of-Life (EOL) scenarios are complex as all processes are different with various product outcomes, particularly because of various unit processes involved in the recycling system. Public knowledge about the disposal of plastic is often misleading. Unlike other materials, plastic wastes are often degraded with inferior properties and contaminated with municipal solid wastes (MSW) restricting the use of one type of EOL scenario and demanding combinations of EOL scenarios to sustainably manage plastic wastes. This complexity demands evaluating the recycling system through various environmental aspects, such as: global warming, energy demand, toxicity, acidification, eutrophication, ozone layer depletion and ozone formation. Establishing economic and environmentally sustainable EOL programmes will be a valuable addition to the whole of society and will result in mitigating plastic pollution, job creation and complementing economic development. Life Cycle Assessment will play a crucial role in comparing various EOL scenarios to estimate environmental impacts through Life cycle impact assessments (LCIA). However, LCA, by itself, is a challenging exercise, particularly because of Life cycle inventory (LCI), system boundaries and LCIA.

A Life cycle assessment method by itself offers various LCIA methods making LCA of plastic recycling challenging for any environmental analyst. Some of the LCIA methods are Eco-Indicator 99, EPS2000, CML 2001, IMPACT 2002, LIME, 2.0, 3.0, TRACI 2.0, ReCiPe, EDIP 2003 and CED (231). The differences between these methods are based on regions and environmental mechanisms, midpoint or endpoint assessments, impact categories, single score or multiple results and inventory data.

## 5.2 Life Cycle Impact Assessment (LCIA)

LCIA is the third phase in LCA methodology which translates life cycle inventory / environmental loads to environmental impacts. The objectives of LCIA are as below (72):

- To enable understanding of inventory data in relation to environmental impacts
- Reduction of mathematical complexity through grouping
- Easier communication and comparability

The stages involved in life cycle impact assessment are classification, characterisation, normalisation, grouping and weighting. A brief explanation on these phases is given below (73):

- Classification: Assigning inventory data to impact category

- Characterisation: This phase translates inventory to quantifiable impacts through characterisation factors.
- Normalisation: This step makes impact indicators comparable to each other.
- Grouping: This step sorts each indicator result into one or more groups or sets. This helps in the analysis and presentation of results.
- Weighting: This is both a qualitative and quantitative procedure in which the relative importance of each environmental impact is weighted against all others. The impacts are expressed according to their relative weighting factors.

These calculations could be conducted manually or through ready-made LCIA methods such as: Eco-Indicator 99, EDIP 2003, CML 2001, TRACI 2.0, EPS 2000, IMPACT 2002, CED, LIME 3.0. Materials and waste management studies have been reported to have used Eco-indicator-99(232)(26), EDIP-2003 (233), CML (234) and CED methodologies (235,236) and other LCIA methods.

The selection of impact categories is based on multiple factors (231), and some of the critical factors are: mid-point or end point impacts, multiple or single score categories and location / region as explained below:

- LCIA methodology could be based on midpoint or endpoint approaches. As shown in Figure 5.2, the key difference between a midpoint and endpoint approach is the point in the environmental mechanism from the emission source to the environmental damage. Midpoint models are close to inventory and endpoint models are close to damage.

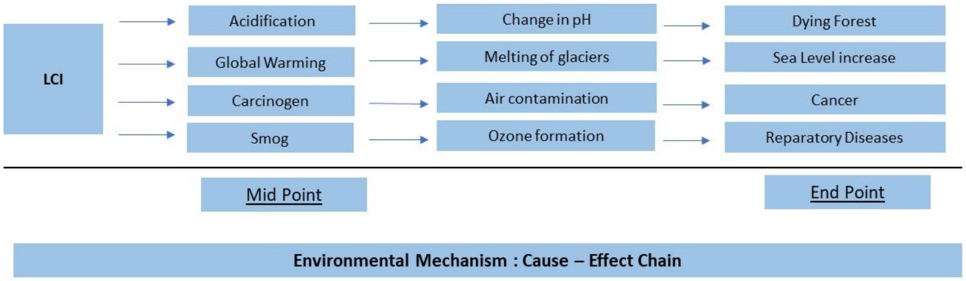


**Figure 5. 2: Schematic explanation of midpoint and endpoint location in an environmental mechanism. Midpoints are easier to identify (such as acidification) and end points are ultimate environmental damages which are not obvious.**

- Some of the LCIA methods are based on a particular region which are normally applied through normalisation factors, and some of the impact categories are based on site-specific cause-effect chain and environmental mechanisms. Normalisation factors for TRACI, CML and EDIP methods are from the USA, Netherlands and Europe respectively. EPS Toxicity models are based on Scandinavian conditions whereas CML is based on European conditions.

- CML reports LCA results in 10 + impact indicators, whereas EDIP reports in 19 different impact indicators. Eco-Indicator-99 reports midpoint results in 10 categories and endpoint in 3 categories as well as in single score. Toxicity is a combination of 3 indicators in EDIP whereas it is only one in CML.

As explained above, not all LCIA methods are similar to each other and this makes comparison complicated. Added to this, a Polymer / Environmental Engineer who is involved in recycling will be given all of these LCIA options from which to choose the most appropriate method. Hence, it is important to understand the effect of LCIA methods on LCA results.

The objective of this study is to:

- Conduct LCA on plastics recycling and evaluate the results through various LCIA methods
- Understand the reason behind the differences between the LCIA results.

The following LCIA methods will be compared in this study:

- CML 2001 and EDIP-2003 in midpoint level with multiple indicators
- Eco-Indicator-99, EDIP-2003 and CED with single score indicators

Cumulative energy demand is primarily based on energy profiles and does not include any other environmental impacts. However, CED is been widely used by researchers and industries to assess the environmental profiles (237).

## 5.3 Methodology Background

A brief background on LCIA methods will be given below:

- Institute of Environmental Sciences of the University of Leiden (CML) Baseline Method 2001
- Environmental Development of Industrial Products, Denmark (EDIP) 2003
- Eco-Indicator-99 (EI-99)
- Cumulative Energy Demand (CED)

### 5.3.1 CML 2 Base Line 2000 Method V2.04

This is a classic midpoint LCIA method based on a ‘Problem Oriented Approach’ developed by the Institute of Environmental Sciences of the University of Leiden. A CML baseline consists of 10 impact categories, shown in Table 5.1 along with measurement units. This method primarily uses European data and restricts impact assessment to midpoints to minimise uncertainties. More details can be obtained from the following methodology literature:

- Jeroen Guinée: Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 2002, 692 pp.
- http://www.cmlca.eu/

| Impact category | Unit |
|---|---|
| Abiotic depletion | kg Sb eq |
| Acidification | kg SO2 eq |
| Eutrophication | kg PO4--- eq |
| Global warming (GWP100) | kg CO2 eq |
| Ozone layer depletion (ODP) | kg CFC-11 eq |
| Human toxicity | kg 1,4-DB eq |
| Fresh water aquatic ecotox. | kg 1,4-DB eq |
| Marine aquatic ecotoxicity | kg 1,4-DB eq |
| Terrestrial ecotoxicity | kg 1,4-DB eq |
| Photochemical oxidation | kg C2H4 |

**Table 5. 1: CML 2001 baseline LCIA method impact**

### 5.3.2 EDIP 2003 Method V1.0

The "Environmental Development of Industrial Products (EDIP)" is an LCIA method developed at the Technical University of Denmark. EDIP 2003 replaces EDIP-97 version with increased environmental coverage and site-specific impact characterisation. An EDIP 2003 model includes dispersion of the substance and its subsequent exposure including assessing environmental sensitivity, and, considering the target situation against exposure limits. This approach decreases uncertainty with more accurate predictions of environmental damage (238).

Human and Eco-toxicity modelling differentiates the EDIP method from other methods. The EDIP method predicts toxicity data from a simple toxic impact data model which does not need large amounts of data (72). This helps to achieve three types of eco-toxicity indicators differentiating acute and chronic damage, and three of types of human toxicity indicators differentiating toxicity in air, water and soil. EDIP 2003 contains a total of 19 impact indicators listed in Table 5.2. More details on EDIP methodology could be obtained from the following literature:

- Henrick Wenzel, Michael Hauschild and Leo Alting: Environmental assessment of products. Vol. 1 - Methodology, tools, techniques and case studies, 544 pp. Chapman & Hall, United Kingdom, 1997, Kluwer Academic Publishers, Hingham, MA. USA.
- Jose Potting and Michael Hauschild: Background for spatial differentiation in life cycle impact assessment – the EDIP2003 methodology. Danish Environmental Protection Agency, Copenhagen, 2004
- Roland Hischier and Bo Weidema: Implementation of life cycle impact assessment methods. Ecoinvent report No. 3, v2.2, Swiss Centre for Life Cycle Inventories, 2010

| **Impact category** | **Measrement Units** |
|---|---|
| Global warming 100a | kg CO2 eq |
| Ozone depletion | kg CFC11 eq |
| Ozone formation (Vegetation) | m2.ppm.h |
| Ozone formation (Human) | person.ppm.h |
| Acidification | m2 |
| Terrestrial eutrophication | m2 |
| Aquatic eutrophication EP(N) | kg N |
| Aquatic eutrophication EP(P) | kg P |
| Human toxicity air | m3 |
| Human toxicity water | m3 |
| Human toxicity soil | m3 |
| Ecotoxicity water chronic | m3 |
| Ecotoxicity water acute | m3 |
| Ecotoxicity soil chronic | m3 |
| Hazardous waste | kg |
| Slags/ashes | kg |
| Bulk waste | kg |
| Radioactive waste | kg |
| Resources (all) | kg |

**Table 5. 2: EDIP 2003 impact indicators**

### 5.3.3 Eco-Indicator-99 V2.05

This is one of the well-known European methods to obtain single scores in LCA. It was developed mainly to support design and development engineers. This an endpoint method, and concentrates on the following three damage assessment areas:

- Human Health measured in DALY* (Disability Adjusted Life Years)
- Eco-system health measured in PAF[#1] and / or PDF[#2] (Potentially Affected / Disappeared Fraction)
- Resources measured in MJ Surplus Energy†

*DALY indicates Disability Adjusted Life Years which means years of disabled living or years of life lost due to impacts

[#1]PAF and [#2]PDF indicates Potentially Affected / Disappeared Fraction which means animals affected by impacts and plant species that disappeared as a result of impacts

†MJ Surplus Energy indicates extra energy that future generations must use to excavate scarce resources

There are various steps involved in processing inventory data into a single score through impact categories. A schematic representation of the Eco-indicator methodology is shown in Figure 5.3.

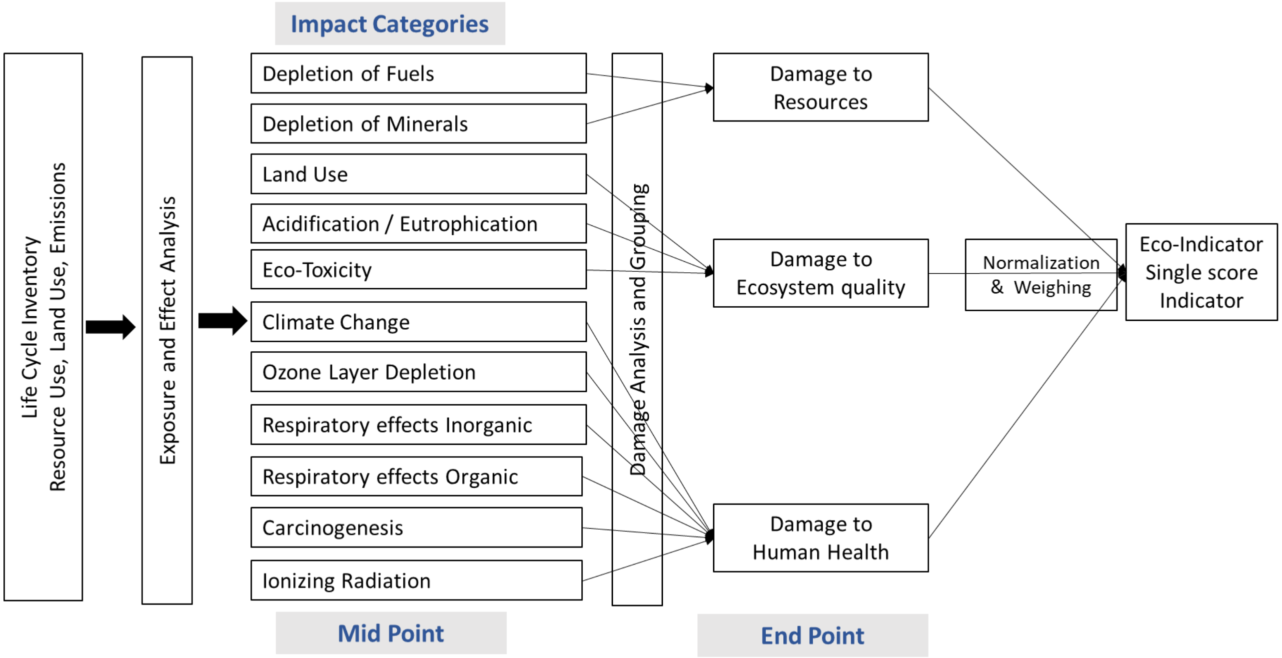


**Figure 5. 3: Eco-Indicator 99 calculation methodology** (55,57,65)

The single score obtained through Eco-indicator methodology is a dimensionless number, Eco-indicator points (Pt) or millipoints (mPt). The Eco-indicator manual defines 1 Pt as ‘*representative of one thousandth of the yearly environmental load of one average European inhabitant’* (57). Based on this weighting, three types of Eco-indicators are derived. Weighting in Eco-indicators is based on cultural perspectives. An Eco-indicator presents three types of weighting approaches:

- Hierarchist
- Individualist
- Egalitarian

Weighting factors in Eco-indicator-99 are based on these cultural attitudes through which an environmental problem is perceived in society. The Egalitarian approach is a long-term precautionary approach with the intention to include all potential issues. The Individualist approach is a short-term and optimistic style – only proven environmental issues are included in the damage. The Hierarchist approach is the midway between these two perspectives based on facts and with scientific and political back-up (72,166). More details can be obtained from following literature:

- PRé Consultants: Eco-Indicator 99 Manual for designers: A damage-oriented method for life cycle impact assessment, 2000
- Mark Goedkoop and Renilde Spriensma: The eco-indicator 99 – A damage-oriented method for life cycle impact assessment. Methodology report, Pré Consultants, 2001

### 5.3.4 Cumulative energy Demand (CED)

Cumulative energy demand is a technique widely used mainly to map direct and indirect use of energy in a process or a product. This is widely used to identify energy savings when considering design, production, use and disposal (238). CED consist of four impact indicators:

- Fossil non-renewable - MJ
- Nuclear non-renewable - MJ
- Renewable Biomass - MJ
- Renewable wind, solar, geothermal - MJ
- Renewable water - MJ

All of these found indicators are weighted and added together to get a single score. More details on CED could be obtained from the following literature:

- Roland Hischier and Bo Weidema: Implementation of life cycle impact assessment methods. Ecoinvent report No. 3, v2.2, Swiss Centre for Life Cycle Inventories, 2010
- VDI 1997: Cumulative Energy Demand - Terms, Definitions, Methods of Calculation In: VDI-Richtlinien 4600. Verein Deutscher Ingenieure, Düsseldorf

Wherever required, publication from Dreyer et al. (239) will be referred where similar comparison been made but in a different application.

## 5.4 Goal

The goal of this study is to compare processing of 1000kg of plastic waste with mechanical recycling and incineration with energy recovery as end of life scenarios through various impact assessment methods

### 5.4.1 Functional Unit

To compare processing of 1000kg of plastic waste (mixture of film and bottle fraction predominantly polyolefin type material) through mechanical recycling and incineration with energy recovery with following impact assessment methods:

- CML 2 Base Line 2000 Method V2.04
- EDIP 2003 V1.0
- Eco-Indicator-99 V2.05
- Cumulative energy Demand (CED) V1.04

to evaluate the effect of above LCIA impacts on above mentioned EOL scenarios through substance and process contribution techniques. Avoided burden to be removed to keep comparison simple and transparent. LCI reported by Kremer et al. (37) to be adopted in this study.

## 5.5 Life Cycle Inventory:

Life cycle inventory for both Mechanical Recycling and Energy Recovery for this study is adopted from Kremer et al. (37). There are studies published (27,84,240) in mechanical recycling and incineration, however, Kremer et al. (37), has published a detailed breakdown of all inventory data of various recycling scenarios such as:

- Five types of feedstock recycling,
- Two types of energy recovery,
- Four types of mechanical recycling options (films and bottles), and
- Three types of mechanical recycling of mixed plastic fractions.

This section covers the inventory of mechanical recycling and incineration with energy recovery scenarios. The approach used in Kremer et al. (37) is the ‘Basket of Benefits Method’. It is difficult to compare two types of recycling systems as their products are not the same, hence the system boundary is expanded by including conventional processes which would have happened because of recycling and will be added as a reference system in the two scenarios. This procedure is being used in LCA studies (241) and also criticised for lack of clarity in ISO14040 (242). Implementing this procedure in 2 or 3 multiple products makes LCA modelling more complicated. Hence this system is being replaced by 'Environmental Credit or Avoided Burden Methodology' as reported in material recycling studies (84,240). The difference between these two methodologies is shown in Figure 5.4.

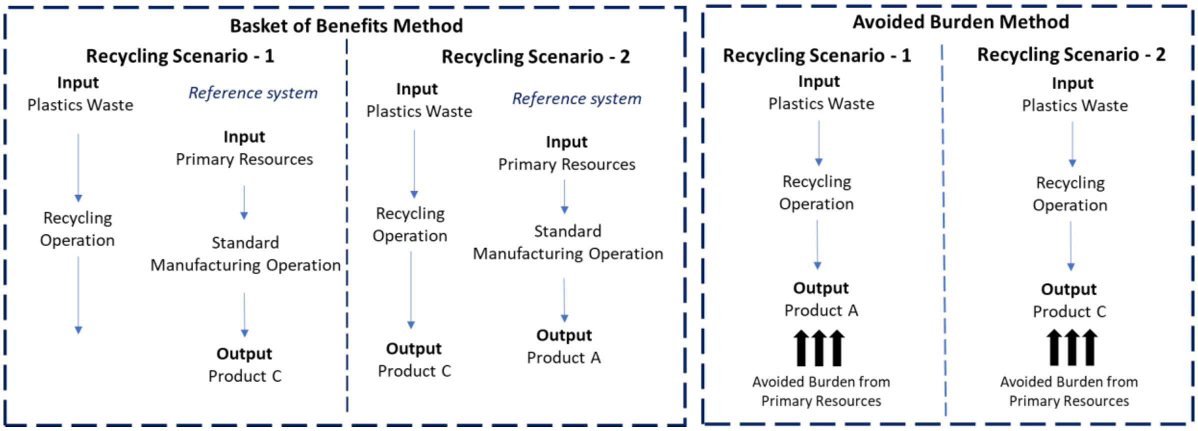


**Figure 5. 4: Comparison of basket of benefits vs. avoided burden methodology**

## 5.5.1 Mechanical Recycling:

The LCI data in mechanical recycling includes data from following steps:

- Internal transport with a forklift and preliminary shredding
- Wet grinding and size reduction: Reducing particle size to a required size range along with cleaning.
- Washing / frictional washing: Multiple washes removes contaminants from recycled plastics
- Density separation: Sink float technique to separate contamination from plastics flakes.
- Drying: Mechanical drying to reduce moisture content to less than 10% followed by thermal drying to bring moisture content to less than 0.4%.
- Extrusion pelletisation: In this process, shredded flakes are melt-mixed at a high temperature to make it homogenous, to release volatile products and to melt-filter any contaminants. The melt stream is normally solidified and pelletized at the end of the extrusion line.
- Effluent: The waste water from various process steps are waste treated in the inherent effluent treatment plant.

Process input-output details are presented in Table 5.3. More details could be found from Kremer et al. (37).

### 5.5.2 Incineration with Energy Recovery

Though mechanical recycling is regarded as a beneficial technique, incineration with energy recovery has the following advantages (96):

- Volume reduction: Decreases volume of waste by 90%
- Stabilization: Incinerator output, ash, is lot more stable than incinerator input
- Energy recovery: Energy recovered from incineration is a source of heat and power which is considered as renewable energy
- Sterilization: Clinical waste incinerated will help the burning off of all pathogens and make it safe for landfill.

Three types of incineration with energy recovery processes available are listed below:

- Fluidised bed combustion (37)
- Municipal solid waste incineration (MSW) (243)
- Co-combustion in cement kilns (244)

Incineration with energy recovery in a municipal solid waste incinerator is chosen for this study as this is the most common incinerator available. As shown in Figure 5.5, there are three-unit processes linked together in this technique:

- Steam Generator
- Steam Utilisation
- Flue Gas Purification plant

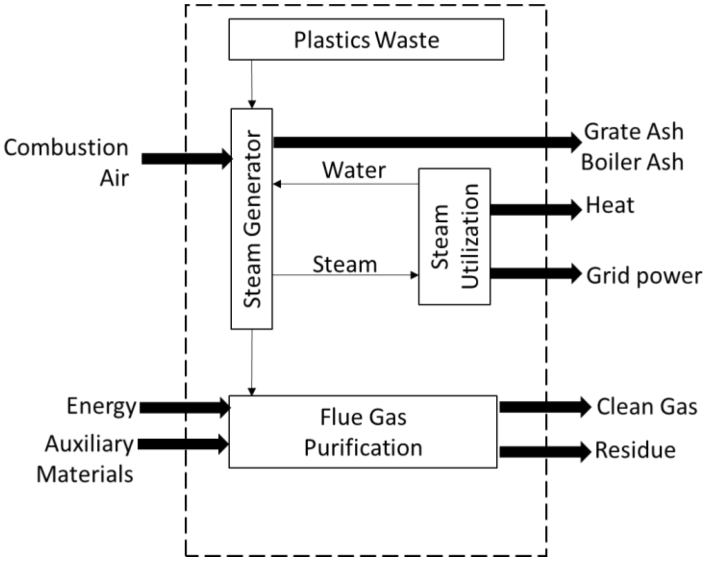


**Figure 5. 5: Incineration with Energy Recovery: Unit Processes** (37)

MSW, along with plastics waste, air for combustion, water for bed ash cooling, and water from steam utilisation are typical inputs. Steam, bed ash, boiler ash and flue gas are the outputs. Flue gas is then passed through the following to meet air quality standards:

- Dust removal in electrostatic precipitator
- Gas scrubbing
- Catalytic reduction of nitrogen oxides
- Entrained bed absorber

Process input-output details are presented in Table 5.4. More details could be found from Kremer et al. (37) which reported the use of allocation and multi-input system to provide the effect of 1000kg of plastic waste fraction from 9000kg of domestic waste.

### 5.5.3 Functional Unit and System Boundary

The functional unit is recycling of 1000kg of plastic waste through both mechanical recycling and incineration with the energy recovery scenario. As shown in the system boundary (Figure 5.6), both the cases use avoided burden as a benefit to credit the recycling process to simplify the comparability.

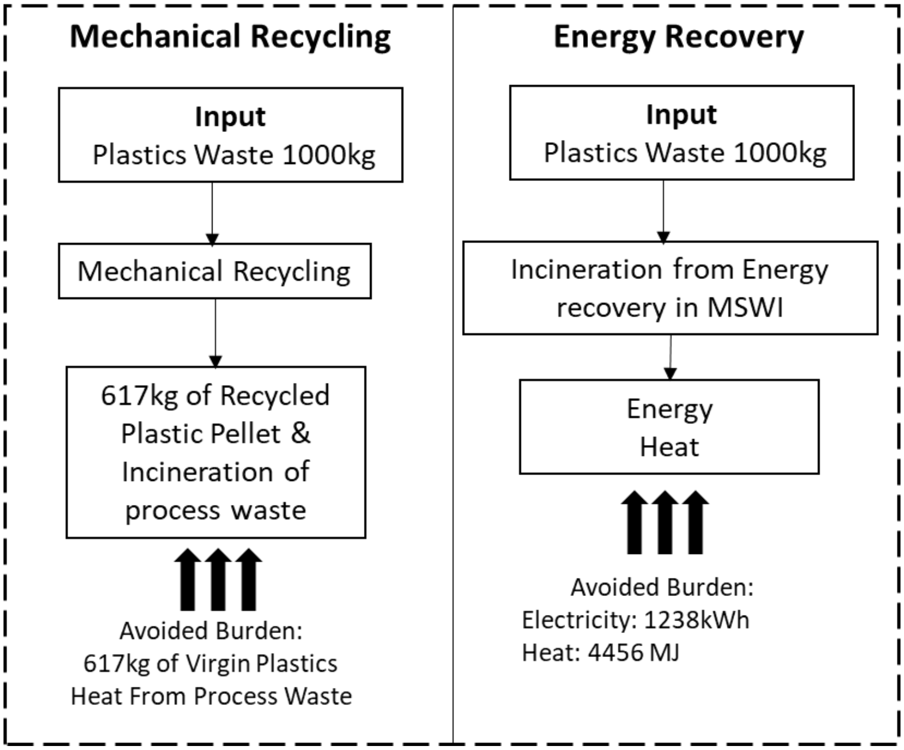


**Figure 5. 6: System boundary**

| Mechanical recycling: LCI Input - Output Data | | | |
|---|---|---|---|
| **Input** | **Value** | **Unit** | **Comments** |
| **Plastics Waste** | 100 | kg | |
| Electricity | 72.42 | kWH | |
| Heat | 6.89 | MJ | via industrial standard Natural gas boiler |
| Water | 237.97 | kg | For Cleaning and seperation |
| Auxilliaries | 0.02 | kg | Defoaming Agents, Disinfectants, Flocculants |
| Additives | 0.25 | kg | |
| Transportation | 200 | km | Used in software as 20tkm; Distance from MRF to Recycling Centre |
| Transportation | 100 | km | Used in software as 10tkm; Transport involved in waste collection |
| **Output** | | | |
| Recycled Pellets | 61.74 | kg | 61.7% Yield - 'Avoided Burden' |
| Mixed Plastics for recycling | 6.3 | kg | Possess Energy value of 30MJ per kg. This would yield 30 x 6.3 = 189MJ heat as avoided burden |
| Waste to Recycling | 38.05 | kg | PET, PVC, PE, Paper, Mixed Plastics, Water and Contaminants; Energy Value: 8.52 MJ/kg; This would yield 323.76 MJ of heat as 'Avoided Burden' |
| Waste to Disposal | 22.11 | kg | Sludge, Industrial Waste, slags, Ashes, Toxic and Non-Toxic Chemicals |
| Effluent for Treatment | 210.07 | kg | |
| | | | |
| **Effluent Composition Adjusted to 210.07 kg of Effluent** | | | |
| BOD5 | 0.168 | kg | |
| COD | 565.075 | kg | |
| Ammonium/Ammonia | 0.017 | kg | |
| Nitrates | 0.138 | kg | |
| Phosphates | 0.061 | kg | |

**Table 5. 3: Mechanical recycling: LCI input – output data** (37)

| Energy Recovery: LCI Input - Output Data (Co-combustion of plastic waste in MSWI) | | | |
|---|---|---|---|
| **Input** | **Value** | **Unit** | **Comments** |
| **Plastics Waste As Collected** | 1335 | kg | This is inclusive of 335kg Sorting Residue |
| **Plastics Waste For Incineration** | 1000 | kg | |
| Electricity | 171 | kWH | |
| Heat | 724 | MJ | via industrial standard Natural gas boiler |
| Water | 741 | kg | Process Water + Ash Cooling Water + Boiler Feed Water |
| Ammonia | 7.7 | kg | |
| Sodium Hydroxide | 13.1 | kg | Average of Mercury, Diaphragm and Membrane Techniques; Simapro doesn't have 100% Sodium Hydroxide Tablets. Hence 2 x 50% = 26.2 Aqueous Sodium Hydroxide is used |
| Activated Coke | 2.31 | kg | |
| Fe(III)Cl | 13.3 | g | |
| TMT-15 | 33.2 | ml | |
| Transportation | 200 | km | Used in software as 200tkm; Distance from MRF to Incineration Centre |
| Transportation | 100 | km | Used in software as 12tkm; Transport involved in moving 120kg residue to 100km |
| Transportation | 100 | km | Used in software as 33.5tkm; Transport involved in moving 335kg residue to 100km |
| **Output** | | | |
| Elecricity | 1238 | kWH | |
| Heat | 4456 | MJ | |
| **Air Emissions in Clean Gas** | | | |
| CO2 | 2392 | kg | |
| H2O | 994 | kg | |
| O2 | 2018 | kg | |
| N2 | 15033 | kg | |
| Nox | 1653 | g | |
| SO2 | 757 | g | |
| HCL | 129 | g | |
| HF | 0.54 | g | |
| NH3 | 21.4 | g | |
| Dust | 16.5 | g | Simapro 7.2 doesnt have dust in emissions. It is been substituted with Particulates |
| TOC | 33.1 | g | |
| CO | 289 | g | |
| PCDD | 0.3 | ug | |
| Hg | 0.02 | g | |
| Cd | 0.08 | g | |
| HM | 2.23 | g | |

**Table 5. 4: Incineration with energy recovery: LCI input – output data**(37)

## 5.6 Life cycle Impact Assessment Results

Height normalised midpoint LCIA results comparing mechanical recycling and energy recovery via:

- CML 2001 (raw data reported in Appendix 4)
- EDIP 2003 (raw data reported in Appendix 4)

are reported in Figures 5.7 and 5.8. Single score results from the following methodology are compared and reported in Figure 5.9.

- Eco-Indicator Hierarchist Method
- Eco-Indicator Egalitarian Method
- Eco-Indicator Individualist Method
- EDIP 2003 Method
- Cumulative Energy Demand (CED) Method

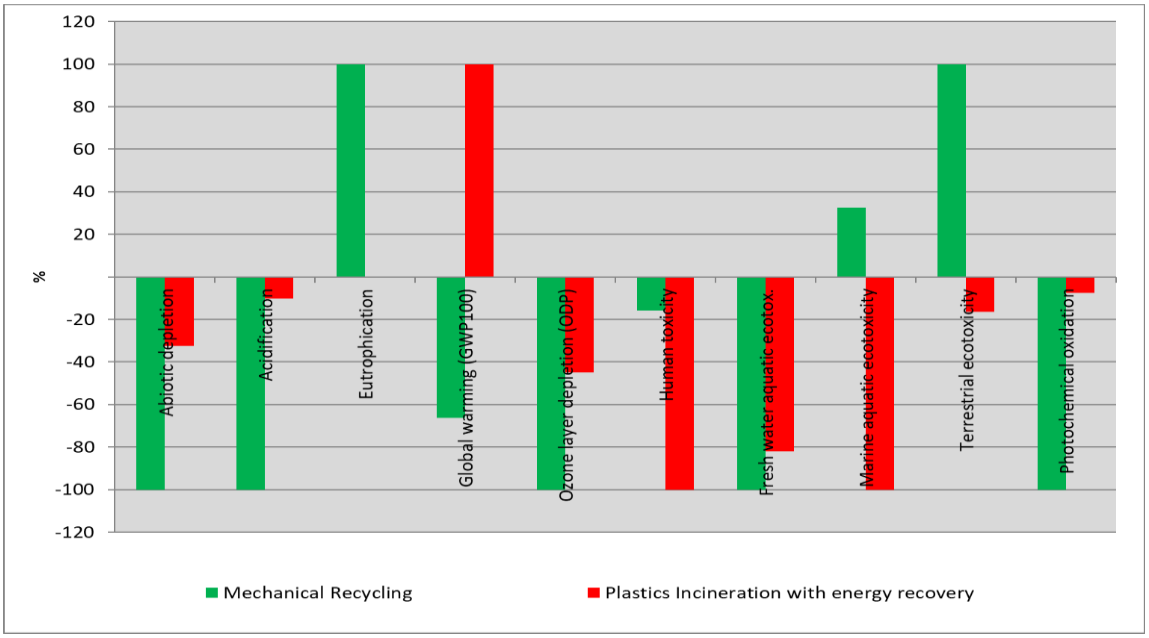


**Figure 5. 7: Mechanical recycling vs. Incineration with energy recovery including avoided burden through CML 2 baseline 2000 method**

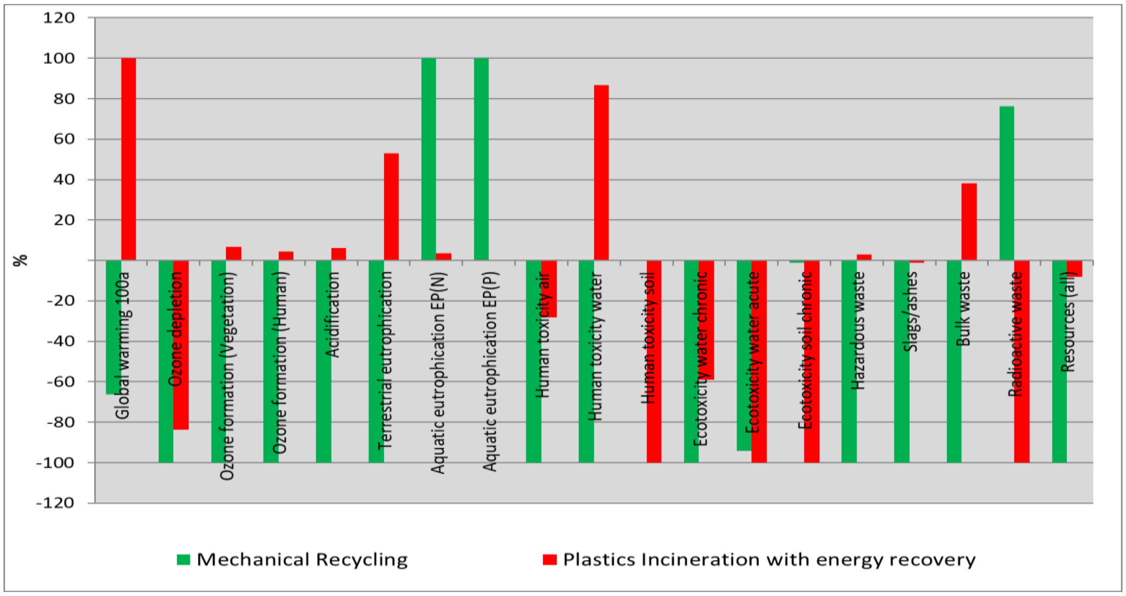


**Figure 5. 8: Mechanical recycling g vs. Energy recovery including avoided burden through EDIP 2003 method**

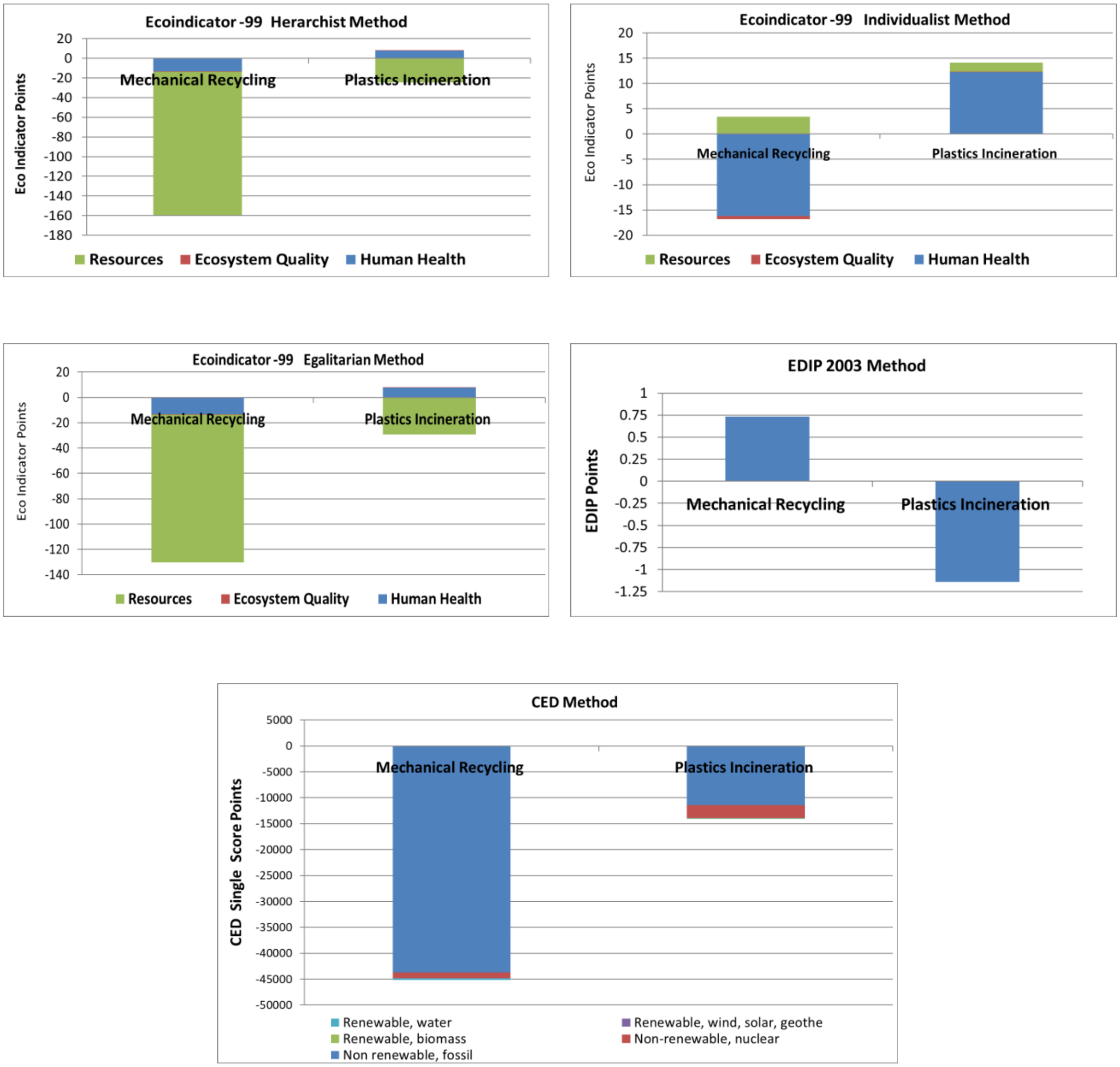


**Figure 5. 9: Single score LCA results of Mechanical recycling and Plastics incineration through various LCIA results inclusive of avoided burden.**

# 5.7 Discussion

## 5.7.1 Comparison of CML Baseline 2001 and EDIP 2003

As reported in Figures 5.7 and 5.8, irrespective of CML or EDIP methods, mechanical recycling has better environmental credentials than energy recovery. This is mainly because of avoided burden which assumes recycled plastic pellets are expected to replace virgin pellets and this outweighs all impacts generated from the recycling operation. It is important to note that most of the impact categories, in both CML and EDIP, are negative, indicating the decrease of environmental impacts. But the consistency and amplitude of negative percentages in Figures 5.7 and 5.8 indicates that virgin plastics manufacturing is a significantly energy-intensive process and reclaiming plastics through simple recycling processes provides huge environmental benefits. This aligns with data (shown in Figure 5.10) published in a recent report by Deloitte (245): the process of obtaining plastics through recycling processes produces 80-90% (approx.) less $CO_2$ when compared against a virgin plastics manufacturing process. This could be due to the number of unit processes involved in the virgin polymer manufacturing method, such as: oil refining, monomer manufacturing, polymerisation, post-polymerisation treatment and twin-screw extrusion. Most of the impact categories favour mechanical recycling except eutrophication and terrestrial eco-toxicity in the CML method. Similarly, most of the impact categories favour mechanical recycling except aquatic marine water toxicity, human toxicity and radioactive waste in EDIP method. The comparison of mechanical recycling and incineration with energy recovery (including avoided burden) could be summarised as below. (Refer to Appendix 4 in relation to below summary.) A detailed discussion on each impact category will be discussed further in this section.

CML 2 Baseline 2000 LCIA Method:

- Most of the impact indicators favour mechanical recycling except eutrophication, human toxicity, marine aquatic eco-toxicity and terrestrial eco-toxicity. 6 out of 10 impact indicators favour mechanical recycling.
- Chemical oxygen demand (COD) from effluent treatment played a significant role in increasing the Eutrophication impact for mechanical recycling. 98% of the total Eutrophication impact is from COD from effluent treatment.
- Higher electricity usage in mechanical recycling led to high marine eco-toxicty via generation of barite contamination leading to higher marine eco-toxicity values.
- Higher electricity usage in mechanical recycling led to terrestrial eco-toxicty via release of Chromium VI (in soil) and Mercury (in air). Chromium VI and Mercury together contributed around 99% of the total impact.

EDIP 2003 Method:

- Similar to the CML method, most of the impact categories favour mechanical recycling. 13 out of 19 impact indicators favour mechanical recycling.

- Nitrates and phosphates emissions in the effluent treatment phase in mechanical recycling influenced the obtaining of higher Eutrophication values (N and P) in mechanical recycling.
- The release of benzene (in air) and iron (in soil) through the electricity generation process led to high human toxicity in soil.
- The release of formaldehyde and aluminium in air through the electricity generation process led to higher chronic soil eco-toxicity.
- Higher radioactive waste values through the electricity generation process led to higher radioactive waste category.

To facilitate method comparison, avoided burden will be excluded from the calculation to provide comparison between mechanical recycling and energy recovery. The LCIA results, after removing avoided burden, are shown in Figures 5.11 and 5.12. Raw data comparing CML and EDIP are grouped and reported in Table 5.5 with CML data as a baseline value. The CML and EDIP methods seem to yield similar outcomes when comparing mechanical recycling and plastics incineration except in the 'resource' category. The outcomes from eco-toxicity are not comparable as they are represented in dissimilar indicators and units. Each impact category will now be compared. For the purpose of identifying the differences between the two LCIA methods, mechanical recycling data will be analysed in detail including process contribution, substance contribution and its related characterisation factor.

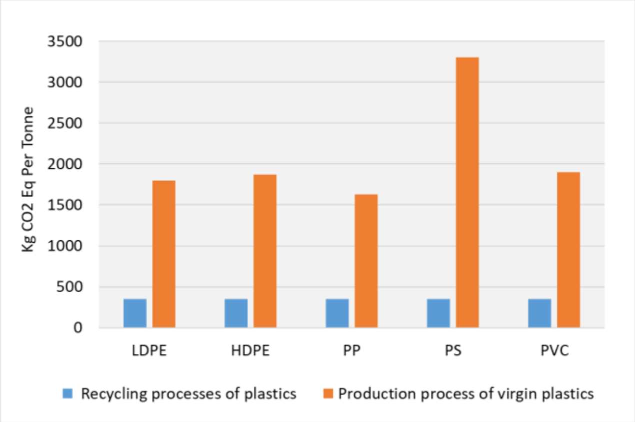


Figure 5. 10: Carbon emission comparison of recycled and virgin plastics manufacturing process (245)

| Method | Impact category | Unit | Mechanical Recycling | Plastics Incineration | Comparison<br>Mechanical Recycling | Comparison<br>Plastics Incineration |
|---|---|---|---|---|---|---|
| CML Baseline | Global warming (GWP100) | kg CO2 eq | 479.99 | 2640.21 | 3.26% | 0.77% |
| EDIP 2003 | Global warming 100a | kg CO2 eq | 495.62 | 2660.46 | | |
| CML Baseline | Abiotic depletion | kg Sb eq | 3.70 | 1.98 | NA | NA |
| EDIP 2003 | Resources (all) | kg | 0.01 | 0.02 | | |
| CML Baseline | Acidification | kg SO2 eq | 1.62 | 2.54 | NA | NA |
| EDIP 2003 | Acidification | m2 | 26.62 | 48.79 | | |
| CML Baseline | Ozone layer depletion (ODP) | kg CFC11 eq | 1.57E-05 | 4.18E-05 | 7.59% | -16.77% |
| EDIP 2003 | Ozone depletion | kg CFC11 eq | 1.69E-05 | 3.48E-05 | | |
| CML Baseline | Photochemical oxidation | kg C2H4 | 0.07 | 0.10 | NA | NA |
| EDIP 2003 | Ozone formation (Vegetation) | m2.ppm.h | 1995.33 | 4120.31 | | |
| EDIP 2003 | Ozone formation (Human) | person.ppm.h | 0.14 | 0.28 | | |
| CML Baseline | Eutrophication | kg PO4--- eq | 126.48 | 0.29 | NA | NA |
| EDIP 2003 | Aquatic eutrophication EP(N) | kg N | 1.96 | 0.21 | | |
| EDIP 2003 | Aquatic eutrophication EP(P) | kg P | 0.18 | 0.00 | | |
| EDIP 2003 | Terrestrial eutrophication | m2 | 23.32 | 56.05 | | |
| CML Baseline | Fresh water aquatic ecotox. | kg 1,4-DB eq | 9.93 | 10.42 | NA | NA |
| CML Baseline | Marine aquatic ecotoxicity | kg 1,4-DB eq | 49180.54 | 31794.34 | | |
| CML Baseline | Terrestrial ecotoxicity | kg 1,4-DB eq | 1.42 | 2.21 | | |
| EDIP 2003 | Ecotoxicity water chronic | m3 | 18580.56 | 16525.66 | NA | NA |
| EDIP 2003 | Ecotoxicity water acute | m3 | 7218.97 | 5341.85 | | |
| EDIP 2003 | Ecotoxicity soil chronic | m3 | 40.85 | 46.77 | | |
| CML Baseline | Human toxicity | kg 1,4-DB eq | 78.76 | 81.77 | NA | NA |
| EDIP 2003 | Human toxicity air | m3 | 2.43E+06 | 2.83E+06 | | |
| EDIP 2003 | Human toxicity water | m3 | 2001.214 | 6411.256 | | |
| EDIP 2003 | Human toxicity soil | m3 | 33.67 | 26.70 | | |

**Table 5. 5: EDIP vs. CML Data Comparison. Comparison column indicates comparison between CML and EDIP 2003 methods with CML as a baseline. NA indicates not applicable as they are of different units.**

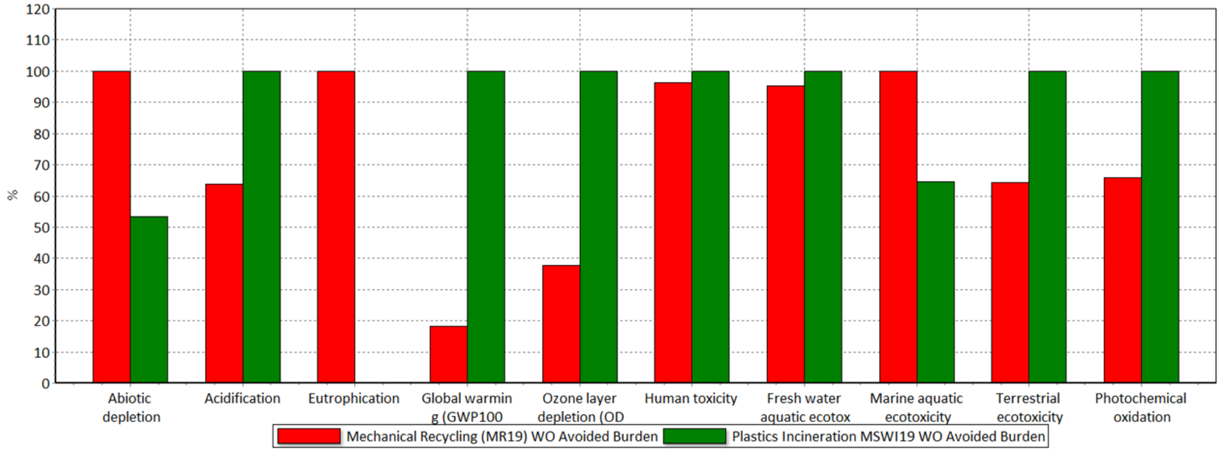


**Figure 5. 11: CML Method - Mechanical Recycling g vs. Incineration with energy recovery excluding avoided burden**

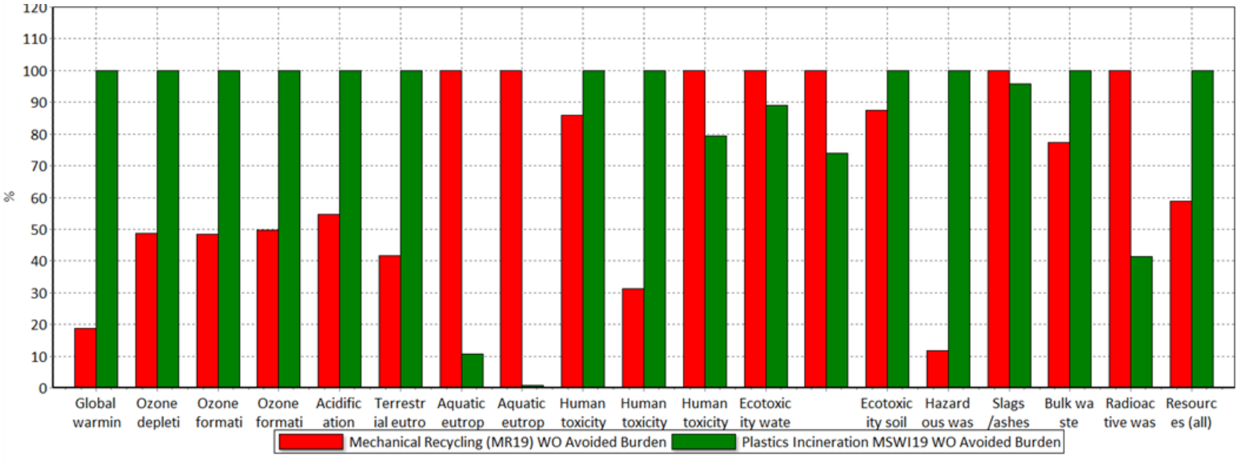


**Figure 5. 12: EDIP Method - Mechanical Recycling vs. Energy Recovery excluding avoided burden**

## 5.7.1.1 Global Warming

As shown in Table 5.5, in both CML and EDIP methods, mechanical recycling scored lower values than incineration. Even though the comparison outcome from CML and EDIP methods are the same, both the methods did not yield the same values. The EDIP method gave 3% and 0.7% higher values than CML for mechanical recycling and incineration, respectively. This is primarily due to the difference in characterisation factors in the EDIP and CML methods. It is interesting to note that electricity usage contributes around 92% of impacts in both the CML and EDIP methods. Process contribution, substance contribution and characterisation factors are shown in Table 5.6, indicating 97% uniformity in contribution in both substances and processes. A negative characterisation factor, -1 for $CO_2$, applied in the CML method from one particular unit process associated with GB electricity usage, caused a difference of around 3.18% on total kg $CO_2$ equivalent obtained via the CML method. The process in which the negative characterisation factor was applied was related to the use of wooden material. The reason behind this negative characterisation factor could be because of the carbon sequestration aspect during tree growth.

|  | CML Results |  | % Process Contribution |  |  | Characterisation Factor kg $CO_2$ Eq |
|---|---|---|---|---|---|---|
|  | **Substance** | **Total** | **Transport** | **Electricity** | **Heat** |  |
| **% Substance Contribution** | Total of all compartments | 100.00 | 6.47 | 92.58 | 0.96 |  |
|  | Remaining substances | 0.15 | 0.04 | 0.11 | 0.00 |  |
|  | Carbon dioxide, fossil | 51.73 | 0.66 | 51.03 | 0.04 | 1 |
|  | Carbon dioxide, fossil | 36.98 | 0.64 | 35.48 | 0.86 | 1 |
|  | Carbon dioxide, fossil | 5.43 | 4.88 | 0.54 | 0.00 | 1 |
|  | Methane, fossil | 4.45 | 0.19 | 4.21 | 0.05 | 23 |
|  | Carbon dioxide, biogenic | 2.92 | 0.01 | 2.91 | 0.00 | 1 |
|  | Sulfur hexafluoride | 0.56 | 0.00 | 0.55 | 0.00 | 22200 |
|  | Dinitrogen monoxide | 0.42 | 0.00 | 0.42 | 0.00 | 296 |
|  | Dinitrogen monoxide | 0.29 | 0.05 | 0.24 | 0.00 | 296 |
|  | Dinitrogen monoxide | 0.25 | 0.00 | 0.25 | 0.00 | 296 |
|  | Carbon dioxide, in air | -3.18 | -0.02 | -3.16 | 0.00 | -1 |

|  | EDIP Results |  | % Process Contribution |  |  | Characterisation Factor kg $CO_2$ Eq |
|---|---|---|---|---|---|---|
|  | Substance | **Total** | **Transport** | **Electricity** | **Heat** |  |
| **% Substance Contribution** | Total of all compartments | 100.00 | 6.31 | 92.76 | 0.93 |  |
|  | Remaining substances | 0.22 | 0.07 | 0.15 | 0.00 | 1 |
|  | Carbon dioxide, fossil | 50.09 | 0.64 | 49.42 | 0.04 | 1 |
|  | Carbon dioxide, fossil | 35.81 | 0.62 | 34.36 | 0.83 | 1 |
|  | Carbon dioxide, fossil | 5.26 | 4.73 | 0.53 | 0.00 | 1 |
|  | Methane, fossil | 4.31 | 0.19 | 4.07 | 0.05 | 23 |
|  | Carbon dioxide, biogenic | 2.83 | 0.01 | 2.82 | 0.00 | 1 |
|  | Sulfur hexafluoride | 0.54 | 0.00 | 0.54 | 0.00 | 22200 |
|  | Dinitrogen monoxide | 0.41 | 0.00 | 0.41 | 0.00 | 296 |
|  | Dinitrogen monoxide | 0.28 | 0.05 | 0.23 | 0.00 | 296 |
|  | Dinitrogen monoxide | 0.24 | 0.00 | 0.24 | 0.00 | 296 |

**Table 5. 6: Global Warming Potential for Mechanical Recycling: Process contribution, substance contribution and characterisation factors for both CML and EDIP methods. Data reported with 0.1% cut-off and reported as % of total value.**

### 5.7.1.2 Resource Depletion

The resource depletion impact category represents the impacts related to consumption of raw materials or resources used in manufacturing a particular product along its whole life cycle. It is called ‘Resources’ in the EDIP method and ‘Abiotic Depletion Potential’ in the CML method. Different ways of resource depletion impact measurement have been reported and are in practice, reflecting the problems of definition (64) – including the methods used in CML and EDIP methods.

As can be seen from Table 5.7, the resources (or resource depletion) category is not straightforward when it comes to comparing with each other as they have different units and are calculated through different mechanisms. The resource in EDIP is a summation of all resources including renewables and non-renewables. The CML method calculates the resource depletion quantity and rate of depletion against reserves and rate of extraction of reference substance and CML method covers only abiotic resources. The standard reference substance used in this category is Antimony (Sb). The CML method favours incineration whereas EDIP favours mechanical recycling. To investigate this, as mentioned at the beginning of this section, the mechanical recycling inventory is chosen. Process contribution and substance contribution analyses indicate that electricity is the major contributor in both the methods. Substance contribution analysis indicates that coal and natural gas are major contributors in the CML method. However, nickel and natural gas are the major contributors in the EDIP method. Substance and process contribution analyses are shown in Table 5.7. Characterisation factors are not compared as EDIP does not have any characterisation factors.

### 5.7.1.3 Acidification

Acidification in the CML method is based on the proton release capability of the compound and is expressed in reference to kg $SO_2$ Equivalent. However, the EDIP method uses areas exposed to acidifying pollutants which are released from the activities and expressed in $m^2$. These differences in units limit the direct comparison of these methods. Irrespective of different measurement techniques, both the methods estimate higher values for incineration than mechanical recycling. This higher value from incineration could be because of emissions from the incineration of plastics.

Process contribution, substance contribution and characterisation factors are shown in Table 5.8. Contribution from electricity usage, transport and heat are approx. 93.5%, 6% and 0.5% respectively for both the CML and EDIP methods. However, the substance contribution analyses are not identical. Sulfur

| % Substance Contribution | **CML Results - Abiotic Depletion Potential** | **% Process Contribution** | | | |
|---|---|---|---|---|---|
| | **Substance** | **Total** | **Transport** | **Electricity** | **Heat** |
| | Total of all compartments | 100.00 | 6.33 | 92.61 | 1.06 |
| | Remaining substances | 0.01 | 0.01 | 0.00 | 0.00 |
| | Coal, hard, unspecified, in ground | 55.03 | 0.48 | 54.54 | 0.00 |
| | Gas, natural, in ground | 35.57 | 0.54 | 33.97 | 1.05 |
| | Oil, crude, in ground | 8.24 | 5.18 | 3.06 | 0.00 |
| | Gas, mine, off-gas, process, coal mining/m3 | 0.76 | 0.01 | 0.76 | 0.00 |
| | Coal, brown, in ground | 0.40 | 0.11 | 0.28 | 0.00 |
| | | | | | |

| % Substance Contribution | **EDIP Results - Resources** | **% Process Contribution** | | | |
|---|---|---|---|---|---|
| | Substance | **Total** | **Transport** | **Electricity** | **Heat** |
| | Total of all compartments | 100.00 | 19.18 | 79.87 | 0.95 |
| | Remaining substances | 0.22 | 0.08 | 0.14 | 0.00 |
| | Nickel, 1.98% in silicates, 1.04% in crude ore, in ground | 37.47 | 11.01 | 26.32 | 0.14 |
| | Gas, natural, in ground | 26.31 | 0.40 | 25.13 | 0.78 |
| | Coal, hard, unspecified, in ground | 13.24 | 0.12 | 13.12 | 0.00 |
| | Oil, crude, in ground | 5.35 | 3.22 | 2.13 | 0.00 |
| | Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36% in crude ore, in ground | 3.66 | 1.23 | 2.43 | 0.01 |
| | Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground | 3.17 | 0.38 | 2.78 | 0.00 |
| | Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground | 2.40 | 0.28 | 2.12 | 0.00 |
| | Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36% in crude ore, in ground | 1.82 | 0.61 | 1.20 | 0.00 |
| | Iron, 46% in ore, 25% in crude ore, in ground | 1.52 | 0.88 | 0.63 | 0.01 |
| | Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83% in crude ore, in ground | 0.92 | 0.11 | 0.81 | 0.00 |
| | Aluminium, 24% in bauxite, 11% in crude ore, in ground | 0.91 | 0.30 | 0.60 | 0.00 |
| | Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground | 0.64 | 0.08 | 0.56 | 0.00 |
| | Gas, mine, off-gas, process, coal mining/m3 | 0.56 | 0.00 | 0.56 | 0.00 |
| | Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39% in crude ore, in ground | 0.48 | 0.06 | 0.42 | 0.00 |
| | Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground | 0.43 | 0.05 | 0.38 | 0.00 |
| | Tin, 79% in cassiterite, 0.1% in crude ore, in ground | 0.37 | 0.27 | 0.10 | 0.00 |
| | Coal, brown, in ground | 0.26 | 0.05 | 0.20 | 0.00 |
| | Manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground | 0.14 | 0.05 | 0.09 | 0.00 |
| | Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81% in crude ore, in ground | 0.13 | 0.02 | 0.12 | 0.00 |

**Table 5. 7: Resource Depletion for Mechanical Recycling: Process contribution and substance contribution for both CML and EDIP methods. Data reported with 0.1% cut-off and reported as % of total value.**

dioxide and Nitrogen oxides are two major contributors in both the CML and EDIP methods but quantity and relative ratios are not same. Hydrogen Chloride and Hydrogen Fluoride, together contribute up to 6.18% in the EDIP method, but not in CML. Further analysis on this subject indicates that the CML methodology document does include HCl and HF (64) and was found in ‘CML all impact categories method’ rather than the CML baseline 2000 method. Simapro guidelines indicate that the CML baseline method has characterisation factors where fate was included (246). Characterisation factors not including fate were extended in ‘CML all impact categories method’.

|  | **CML Method - Acidification** | % Process Contribution |  |  |  | **Characterisation Factors kg $SO_2$ Eq/kg** |
|---|---|---|---|---|---|---|
| % Substance Contribution | Substance | **Total** | **Transport** | **Electricity** | **Heat** |  |
|  | Total of all compartments | 100.0 | 6.0 | 93.8 | 0.2 |  |
|  | Remaining substances | 0.0 | 0.0 | 0.0 | 0.0 |  |
|  | Sulfur dioxide | 62.7 | 1.7 | 60.9 | 0.1 | 1.2 |
|  | Nitrogen oxides | 16.1 | 0.5 | 15.5 | 0.0 | 0.5 |
|  | Sulfur dioxide | 8.9 | 0.6 | 8.3 | 0.0 | 1.2 |
|  | Nitrogen oxides | 6.1 | 0.1 | 5.9 | 0.1 | 0.5 |
|  | Nitrogen oxides | 4.8 | 2.9 | 2.0 | 0.0 | 0.5 |
|  | Ammonia | 0.8 | 0.0 | 0.8 | 0.0 | 1.6 |
|  | Sulfur dioxide | 0.4 | 0.2 | 0.1 | 0.0 | 1.2 |
|  | Ammonia | 0.2 | 0.0 | 0.2 | 0.0 | 1.6 |

|  | **EDIP Method - Acidification** | % Process Contribution |  |  |  | **Characterisation Factors $m^2$/kg** |
|---|---|---|---|---|---|---|
| % Substance Contribution | Substance | **Total** | **Transport** | **Electricity** | **Heat** |  |
|  | Total of all compartments | 100.00 | 5.98 | 93.82 | 0.20 |  |
|  | Remaining substances | 0.13 | 0.04 | 0.08 | 0.01 |  |
|  | Sulfur dioxide | 56.25 | 1.49 | 54.65 | 0.11 | 17.2 |
|  | Nitrogen oxides | 16.80 | 0.51 | 16.27 | 0.02 | 13.1 |
|  | Sulfur dioxide | 7.97 | 0.54 | 7.42 | 0.01 | 17.2 |
|  | Nitrogen oxides | 6.38 | 0.12 | 6.20 | 0.06 | 13.1 |
|  | Nitrogen oxides | 5.07 | 3.00 | 2.07 | 0.00 | 13.1 |
|  | Hydrogen chloride | 3.59 | 0.02 | 3.56 | 0.00 | 62 |
|  | Hydrogen fluoride | 2.47 | 0.01 | 2.46 | 0.00 | 113 |
|  | Ammonia | 0.73 | 0.04 | 0.69 | 0.00 | 23.1 |
|  | Sulfur dioxide | 0.32 | 0.19 | 0.12 | 0.00 | 17.7 |
|  | Ammonia | 0.17 | 0.00 | 0.17 | 0.00 | 23.1 |
|  | Hydrogen chloride | 0.12 | 0.01 | 0.11 | 0.00 | 62 |

**Table 5. 8: Acidification Potential for Mechanical Recycling: Process contribution, substance contribution and characterisation factors for both CML and EDIP methods. Data reported with 0.1% cut-off and reported as % of total value**

### 5.7.1.4 Ozone Layer Depletion (OLD)

Ozone is a harmful pollutant affecting human health and plants when present in the lower atmosphere. When present in an upper atmosphere, the ozone layer filters harmful ultraviolet radiation from the sun. The thinning of ozone layer is reported to be due to the release of CFCs and Halons (42).

In both CML and EDIP, OLD is evaluated in kg CFC-11 equivalent. In both the cases, mechanical recycling yielded lower results than incineration. Comparison between methods indicates that CML yielded higher values than EDIP in mechanical recycling and vice versa in incineration. A process contribution analysis in mechanical recycling indicates that electricity generation is the major contributor in both CML and EDIP methods. A substance contribution analysis indicates that Halon 1301, Halon 1211 and CFC-114 are the major contributors in both the CML and EDIP methods. As shown in Table 5.9, the differences in results are possibly due to characterisation factors and / or inventory coverage.

| (%) Substance Contribution | **CML Method: Ozone Layer Depletion Potential** | **(%) Process Contribution** | | | | Characterisation Factor kg CFC11 per kg |
|---|---|---|---|---|---|---|
| | **Substance** | **Total** | **Transport** | **Electricity** | **Heat** | |
| | Total of all compartments | 100.00 | 32.55 | 63.89 | 3.56 | |
| | Remaining substances | 0.03 | 0.01 | 0.01 | 0.00 | |
| | Methane, bromotrifluoro-, Halon 1301 | 49.97 | 31.56 | 18.38 | 0.03 | 12 |
| | Methane, bromochlorodifluoro-, Halon 1211 | 31.95 | 0.58 | 27.93 | 3.45 | 51 |
| | Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114 | 16.05 | 0.22 | 15.82 | 0.00 | 0.85 |
| | Methane, chlorodifluoro-, HCFC-22 | 1.20 | 0.02 | 1.10 | 0.08 | 0.034 |
| | Methane, tetrachloro-, CFC-10 | 0.80 | 0.15 | 0.64 | 0.00 | 1.5 |

| (%) Substance Contribution | **EDIP Method: Ozone Layer Depletion Potential** | **(%) Process Contribution** | | | | Characterisation Factor kg CFC11 per kg |
|---|---|---|---|---|---|---|
| | **Substance** | **Total** | **Transport** | **Electricity** | **Heat** | |
| | Total of all compartments | 100.0 | 30.3 | 65.8 | 3.9 | |
| | Remaining substances | 0.0 | 0.0 | 0.0 | 0.0 | |
| | Methane, bromotrifluoro-, Halon 1301 | 46.4 | 29.3 | 17.1 | 0.0 | 12 |
| | Methane, bromochlorodifluoro-, Halon 1211 | 34.9 | 0.6 | 30.5 | 3.8 | 6 |
| | Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114 | 16.5 | 0.2 | 16.3 | 0.0 | 0.94 |
| | Methane, chlorodifluoro-, HCFC-22 | 1.6 | 0.0 | 1.5 | 0.1 | 0.05 |
| | Methane, tetrachloro-, CFC-10 | 0.5 | 0.1 | 0.4 | 0.0 | 0.73 |

**Table 5. 9: Ozone Layer Depletion Potential for Mechanical Recycling: Process contribution, substance contribution and characterisation factors for both CML and EDIP methods. Data reported with 0.1% cut-off and reported as % of total value.**

### 5.7.1.5 Photochemical oxidants formation:

Photochemical oxidant formation is a single indicator in the CML method whereas it is covered in two categories in EDIP, as: Ozone formation (Vegetation) and Ozone formation (Human). The measurement unit in CML is kg $C_2H_4$ equivalent, whereas it is measured as $m^2$.ppm.h (Vegetation) and person.ppm.h (Human). These differences make a comparison challenging.

Photochemical oxidants are secondary pollutants (Ozone) formed from Nitrogen oxides, VOC, and hydrocarbons in the presence of sunlight. Photochemical oxidants generally cause smog and various respiratory-related problems in humans. As reported by Dreyer et al. (239), the CML method uses models established based on Central European conditions, whereas the EDIP 97 (the previous version to the EDIP 2003) method is based on Scandinavian conditions. However, the EDIP 2003 (EDIP 97 had only one impact category) method classifies this impact into two categories: Vegetation and Human Exposure and characterisation values from RAINS model (247). Two categories in this impact allow to estimate individual damages to humans and plants. The impact on vegetation is based on the concentration of adverse chemicals over which it affects certain plant species and is measured in **$m^2$.ppm.h**. Human exposure, measured in **person.ppm.h**, is based on the reaction of high concentrations of photo-chemicals or ozone in combination with a high speed of respired air leading to transport of ozone deep into the lungs and a reaction with tissue macromolecules causing respiratory illnesses (62).

Hauschild et al. (63) compared various photochemical ozone formation methods including CML and EDIP 2003 which adds more explanation to this impact category. Even though both CML and EDIP are mid-point models, CML leans more towards the source of the emission whereas EDIP 2003 leans more towards damages with options to differentiate damages to humans and plants. Characterisation factors and photochemical ozone formation potential (POCP) in the CML method are obtained from a 5-day trajectory model of volatile organic content (VOC) transportation above Europe based on increased amounts of ozone production due to increased amounts of VOC emissions. EDIP 2003 uses the RAINS model to obtain characterisation factors, and impacts on plants and animals were differentiated based on deposition areas (248).

With all these different mechanisms and units of measurement, in both the CML and EDIP methods, mechanical recycling seems to score lower values. As shown in Table 5.10, the process contribution analysis indicates that electricity generation is the major contributor in both the methods. However, the substance contribution analysis indicates that Nitrogen oxides and methane are the major contributors in the EDIP method, whereas Sulphur di-oxide is the major contributor in the CML method. The difference in substances contributing towards the impacts could be because of differences in the underlying meaning and mechanism of this impact category. EDIP indicators are more towards damages, and the CML method presents cumulative photochemical oxidation-causing figures.

| | CML - Photochemical Oxidation | Process Contribution in % | | | |
|---|---|---|---|---|---|
| | Substance | **Total** | **Transport** | **Electricity** | **Heat** |
| | Total of all compartments | 100.00 | 6.33 | 93.18 | 0.48 |
| | Remaining substances | 0.82 | 0.21 | 0.60 | 0.01 |
| Substance Contribution (%) | Sulfur dioxide | 62.40 | 1.65 | 60.63 | 0.12 |
| | Sulfur dioxide | 8.84 | 0.60 | 8.23 | 0.01 |
| | Methane, fossil | 8.57 | 0.37 | 8.10 | 0.10 |
| | Carbon monoxide, fossil | 3.17 | 1.57 | 1.59 | 0.01 |
| | Pentane | 2.60 | 0.43 | 2.13 | 0.05 |
| | Carbon monoxide, fossil | 2.50 | 0.19 | 2.30 | 0.01 |
| | Hexane | 1.88 | 0.20 | 1.68 | 0.00 |
| | Butane | 1.84 | 0.30 | 1.52 | 0.03 |
| | Carbon monoxide, fossil | 1.54 | 0.09 | 1.44 | 0.02 |
| | Ethane | 1.25 | 0.02 | 1.17 | 0.06 |
| | Propane | 0.75 | 0.15 | 0.60 | 0.00 |
| | Ethane | 0.73 | 0.03 | 0.70 | 0.00 |
| | Benzene | 0.49 | 0.00 | 0.48 | 0.00 |
| | Propane | 0.45 | 0.01 | 0.42 | 0.03 |
| | Sulfur dioxide | 0.35 | 0.21 | 0.14 | 0.00 |
| | Toluene | 0.31 | 0.00 | 0.31 | 0.00 |
| | Butane | 0.28 | 0.01 | 0.27 | 0.01 |
| | Pentane | 0.23 | 0.00 | 0.23 | 0.00 |
| | Carbon monoxide, biogenic | 0.22 | 0.07 | 0.15 | 0.00 |
| | Toluene | 0.19 | 0.08 | 0.10 | 0.01 |
| | Formaldehyde | 0.17 | 0.00 | 0.16 | 0.01 |
| | Heptane | 0.16 | 0.10 | 0.06 | 0.00 |
| | Ethene | 0.12 | 0.04 | 0.08 | 0.00 |
| | Formaldehyde | 0.12 | 0.00 | 0.12 | 0.00 |

| | EDIP-Photochemical Oxidation (Vigitation) | | Process Contribution in % | | |
|---|---|---|---|---|---|
| Substance Contribution (%) | Substance | **Total** | **Transport** | **Electricity** | **Heat** |
| | Total of all compartments | 100.00 | 12.49 | 87.03 | 0.48 |
| | Remaining substances | 1.64 | 0.26 | 1.35 | 0.02 |
| | Nitrogen oxides | 46.91 | 1.43 | 45.44 | 0.05 |
| | Nitrogen oxides | 17.83 | 0.34 | 17.32 | 0.17 |
| | Methane, fossil | 16.76 | 0.73 | 15.84 | 0.19 |
| | Nitrogen oxides | 14.16 | 8.36 | 5.79 | 0.01 |
| | NMVOC | 1.47 | 0.62 | 0.81 | 0.04 |
| | NMVOC | 1.02 | 0.64 | 0.38 | 0.00 |
| | Carbon monoxide, fossil | 0.21 | 0.10 | 0.10 | 0.00 |

| | EDIP-Photochemical Oxidation (Humans) | | Process Contribution in % | | |
|---|---|---|---|---|---|
| Substance Contribution (%) | Substance | **Total** | **Transport** | **Electricity** | **Heat** |
| | Total of all compartments | 100.00 | 12.44 | 87.05 | 0.51 |
| | Remaining substances | 1.67 | 0.30 | 1.34 | 0.03 |
| | Nitrogen oxides | 44.94 | 1.37 | 43.53 | 0.04 |
| | Methane, fossil | 19.40 | 0.84 | 18.34 | 0.22 |
| | Nitrogen oxides | 17.08 | 0.33 | 16.59 | 0.16 |
| | Nitrogen oxides | 13.56 | 8.01 | 5.54 | 0.01 |
| | NMVOC | 1.71 | 0.72 | 0.94 | 0.05 |
| | NMVOC | 1.18 | 0.74 | 0.44 | 0.00 |
| | Carbon monoxide, fossil | 0.24 | 0.12 | 0.12 | 0.00 |
| | Xylene | 0.21 | 0.00 | 0.21 | 0.00 |

**Table 5. 10: Photochemical Oxidant formation for Mechanical Recycling: Process contribution, substance contribution and characterisation factors for both CML and EDIP (Humans and Vegetation) methods. Data reported with 0.2% cut-off and reported as % of total value.**

### 5.7.1.6 Eutrophication

Eutrophication is associated with high levels of nutrients, generally N and P, ending up in water bodies leading to the enrichment of nutrients and increased biological growth and activity. Algal growth in water bodies is a typical example of increased biological activity. This increased biological activity leads to oxygen depletion in the bottom layers of the lakes and coastal waters affecting the survival of aquatic animals.

The CML method measures Eutrophication as a single impact as kg $PO_4$ Eq, whereas EDIP measures Eutrophication in three impact categories as Aquatic Eutrophication in Kg(P) and Kg(N) and Terrestrial Eutrophication in $m^2$. EDIP separates impacts into nitrogenous and phosphorous categories to facilitate site-specific impact assessment.

Excepting terrestrial Eutrophication, mechanical recycling seems to have significantly higher Eutrophication values in both CML and EDIP methods. This could be because of wastewater treatment and Chemical Oxygen Demand (COD) from the effluent treatment phase. Hauschild et al. (63) indicated that there are three types of factors that are directly affecting Eutrophication: N in air, N and P in Water and Organic emissions in water (BOD and COD)(63). Biological oxygen demand (BOD) and COD are linked to oxygen consumption for the degradation of organic compounds (64). COD in CML, Nitrate in EDIP Eutrophication (N) and Phosphate in EDIP Eutrophication (P) contribute around 98.3%, 95.5% and 99.5% of total impact respectively. The possible reason could be due to its underlying rationale of impact definition: Eutrophication N and P measures contribution from N and P, and CML measures all eutrophication causing emissions together. In the CML method, apart from COD, the remaining impacts are from nitrates and phosphates.

Terrestrial Eutrophication is covered only in the EDIP method and covers atmospheric deposition of nitrogen compounds which is reported to affect the growth of plants and trees. Even though other impact categories favour incineration, terrestrial Eutrophication measurements indicate that the ammonia emission in the incineration process has a higher impact and favours mechanical recycling.

### 5.7.1.7 Eco-Toxicity

This impact category covers the impact of air pollutants affecting fresh water, marine water and terrestrial eco-Systems. The CML method measures this impact through three independent impact categories in kg 1,4-Dichlorobenzene equivalents (kg 1,4 DB eq). EDIP measures ecotoxicity in three compartments: Water Acute, Water Chronic and Soil Chronic based on (Effective concentration 50%)

EC50 values or (No Observed Effect Concentration) NOEC values and reported as $m^3$ volume of substance and respective characterisation factors to convert them to volumes in $m^3$ (248).

As shown in Table 5.11, two CML eco-toxicity impact categories favour mechanical recycling whereas three EDIP and one CML eco-toxicity impact categories favour incineration. A contribution analysis is shown in Table 5.11 to understand the underpinning differences. On an overall basis, transportation and electricity seems to have had significant influence in contributing towards eco-toxicity.

| Major Contribution Factor | Impact Category |
|---|---|
| Chemicals and Electricity used in Incineration | CML Method Fresh Water Eco -Toxicity |
| Electricity and Transport used in Mechanical recycling | CML Method Marine Water Eco -Toxicity |
| Chemicals used in Incineration | CML Method Terrestrial Eco –Toxicity |
| Electricity used in Mechanical Recycling | EDIP Method chronic water ecotoxicity |
| Electricity used in Mechanical Recycling | EDIP Method acute water ecotoxicity |
| Electricity used in Mechanical Recycling | EDIP Method Chronic ecotoxicity |

**Table 5. 11: Contribution Analysis in Eco-Toxicity Impact Indicator**

### 5.7.1.8 Human Toxicity:

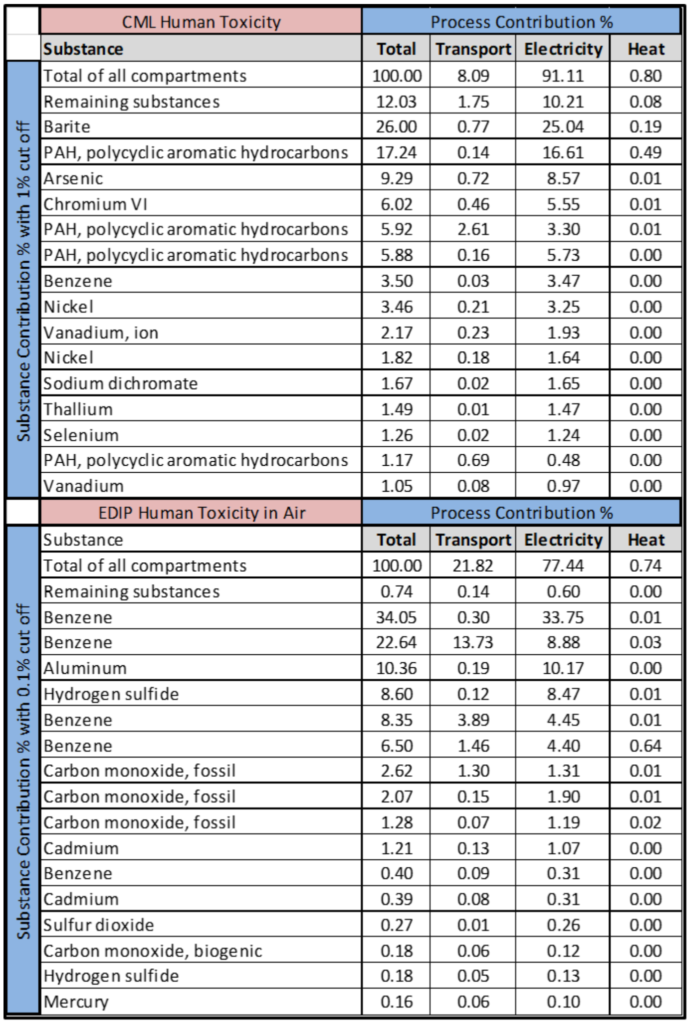
This impact category is very similar to eco-toxicity, focusing on toxic emissions, and uses the same measurement units in both the CML and EDIP methods. All of the impact categories, inclusive of CML and EDIP, favour mechanical recycling except one of the EDIP impact categories (Human Toxicity in soil) which favours incineration. Table 5.12 shows the contribution analysis on the process and its impact on Human Toxicity. A detailed breakdown is presented in Table 5.13.

| Contribution Factor | Impact Category |
|---|---|
| Chemicals and Electricity used in Incineration | CML Method Human Toxicity |
| Electricity used in Mechanical Recycling | CML Method Human Toxicity |
| Electricity used in Mechanical Recycling | EDIP Human toxicity air |
| Electricity used in Mechanical Recycling | EDIP Human toxicity Water |
| Electricity used in Mechanical Recycling | EDIP Human toxicity Soil |
| Emission from Incineration, Chemicals and Electricity used in Incineration | EDIP Human toxicity air |
| Emission from Incineration, Chemicals and Electricity used in Incineration | EDIP Human toxicity Water |
| Emission from Incineration, Chemicals and Electricity & Heat used in Incineration | EDIP Human toxicity Soil |

**Table 5. 12: Contribution Analysis in Human - Toxicity Impact Indicator**

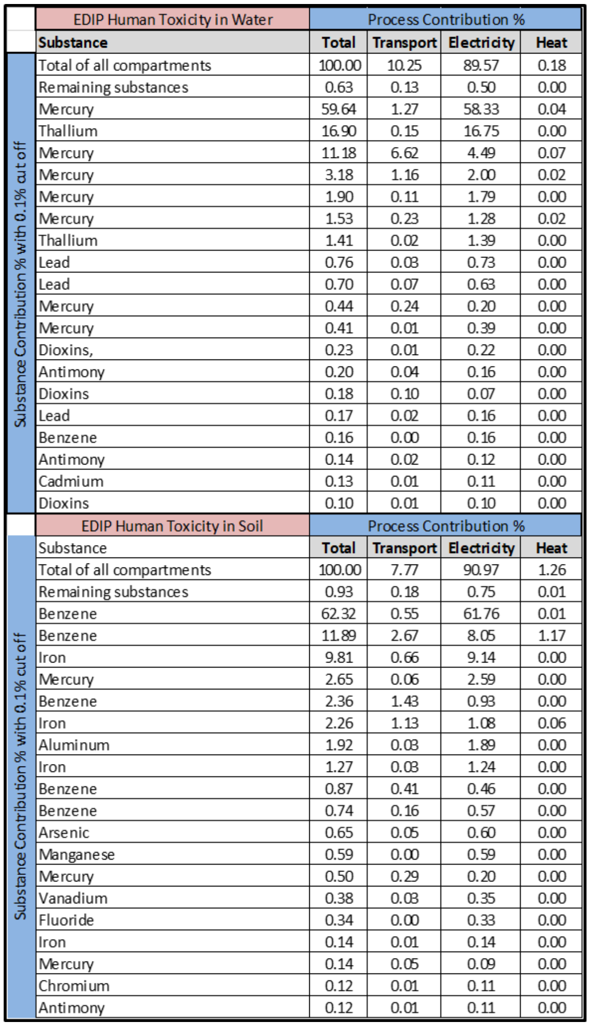
The reverse phenomenon is found in Human Toxicity in soil and indicates the difference in the mechanism of calculation. The substance contribution towards toxicity indicates that Benzene emissions from electricity generation in mechanical recycling are around 75% of the total value. Benzene did contribute towards human toxicity in soil (in incineration), however, only around 50% was from chemicals, electricity and heat. A substance and process contribution analysis (Refer Figure 5.13) on Human Toxicity is presented as follows:

- Barite is one of the top contributors in CML ecotoxicity. The source of barite was from the electricity process, particularly, from onshore or offshore oil exploration production processes. The application of barite is originally to increase drilling fluid density and drilling waste is the source of barite which is highly toxic.
- PAH (Polycyclic aromatic hydrocarbon), another top contributor, was found to be from electricity generation through natural gas burnt in power plants. PAH is most likely to be from airborne emissions from natural gas power plant emissions.
- Benzene, one of the top contributors in EDIP (Human Toxicity Air and Soil), was found to be predominantly from the coke oven gas electricity generation process.
- Mercury and Thallium are the top contributors in Human toxicity water in the EDIP method. Mercury was found to be from emissions in burning coal in power plants. Thallium is from the disposal of residual material after the burning of hard coal ash. This is primarily due to leachate emissions to water.



| | CML Human Toxicity | Process Contribution % | | | |
|---|---|---|---|---|---|
| | **Substance** | **Total** | **Transport** | **Electricity** | **Heat** |
| Substance Contribution % with 1% cut off | Total of all compartments | 100.00 | 8.09 | 91.11 | 0.80 |
| | Remaining substances | 12.03 | 1.75 | 10.21 | 0.08 |
| | Barite | 26.00 | 0.77 | 25.04 | 0.19 |
| | PAH, polycyclic aromatic hydrocarbons | 17.24 | 0.14 | 16.61 | 0.49 |
| | Arsenic | 9.29 | 0.72 | 8.57 | 0.01 |
| | Chromium VI | 6.02 | 0.46 | 5.55 | 0.01 |
| | PAH, polycyclic aromatic hydrocarbons | 5.92 | 2.61 | 3.30 | 0.01 |
| | PAH, polycyclic aromatic hydrocarbons | 5.88 | 0.16 | 5.73 | 0.00 |
| | Benzene | 3.50 | 0.03 | 3.47 | 0.00 |
| | Nickel | 3.46 | 0.21 | 3.25 | 0.00 |
| | Vanadium, ion | 2.17 | 0.23 | 1.93 | 0.00 |
| | Nickel | 1.82 | 0.18 | 1.64 | 0.00 |
| | Sodium dichromate | 1.67 | 0.02 | 1.65 | 0.00 |
| | Thallium | 1.49 | 0.01 | 1.47 | 0.00 |
| | Selenium | 1.26 | 0.02 | 1.24 | 0.00 |
| | PAH, polycyclic aromatic hydrocarbons | 1.17 | 0.69 | 0.48 | 0.00 |
| | Vanadium | 1.05 | 0.08 | 0.97 | 0.00 |

| | EDIP Human Toxicity in Air | Process Contribution % | | | |
|---|---|---|---|---|---|
| | Substance | **Total** | **Transport** | **Electricity** | **Heat** |
| Substance Contribution % with 0.1% cut off | Total of all compartments | 100.00 | 21.82 | 77.44 | 0.74 |
| | Remaining substances | 0.74 | 0.14 | 0.60 | 0.00 |
| | Benzene | 34.05 | 0.30 | 33.75 | 0.01 |
| | Benzene | 22.64 | 13.73 | 8.88 | 0.03 |
| | Aluminum | 10.36 | 0.19 | 10.17 | 0.00 |
| | Hydrogen sulfide | 8.60 | 0.12 | 8.47 | 0.01 |
| | Benzene | 8.35 | 3.89 | 4.45 | 0.01 |
| | Benzene | 6.50 | 1.46 | 4.40 | 0.64 |
| | Carbon monoxide, fossil | 2.62 | 1.30 | 1.31 | 0.01 |
| | Carbon monoxide, fossil | 2.07 | 0.15 | 1.90 | 0.01 |
| | Carbon monoxide, fossil | 1.28 | 0.07 | 1.19 | 0.02 |
| | Cadmium | 1.21 | 0.13 | 1.07 | 0.00 |
| | Benzene | 0.40 | 0.09 | 0.31 | 0.00 |
| | Cadmium | 0.39 | 0.08 | 0.31 | 0.00 |
| | Sulfur dioxide | 0.27 | 0.01 | 0.26 | 0.00 |
| | Carbon monoxide, biogenic | 0.18 | 0.06 | 0.12 | 0.00 |
| | Hydrogen sulfide | 0.18 | 0.05 | 0.13 | 0.00 |
| | Mercury | 0.16 | 0.06 | 0.10 | 0.00 |



| | EDIP Human Toxicity in Water | Process Contribution % | | | |
|---|---|---|---|---|---|
| | **Substance** | **Total** | **Transport** | **Electricity** | **Heat** |
| Substance Contribution % with 0.1% cut off | Total of all compartments | 100.00 | 10.25 | 89.57 | 0.18 |
| | Remaining substances | 0.63 | 0.13 | 0.50 | 0.00 |
| | Mercury | 59.64 | 1.27 | 58.33 | 0.04 |
| | Thallium | 16.90 | 0.15 | 16.75 | 0.00 |
| | Mercury | 11.18 | 6.62 | 4.49 | 0.07 |
| | Mercury | 3.18 | 1.16 | 2.00 | 0.02 |
| | Mercury | 1.90 | 0.11 | 1.79 | 0.00 |
| | Mercury | 1.53 | 0.23 | 1.28 | 0.02 |
| | Thallium | 1.41 | 0.02 | 1.39 | 0.00 |
| | Lead | 0.76 | 0.03 | 0.73 | 0.00 |
| | Lead | 0.70 | 0.07 | 0.63 | 0.00 |
| | Mercury | 0.44 | 0.24 | 0.20 | 0.00 |
| | Mercury | 0.41 | 0.01 | 0.39 | 0.00 |
| | Dioxins, | 0.23 | 0.01 | 0.22 | 0.00 |
| | Antimony | 0.20 | 0.04 | 0.16 | 0.00 |
| | Dioxins | 0.18 | 0.10 | 0.07 | 0.00 |
| | Lead | 0.17 | 0.02 | 0.16 | 0.00 |
| | Benzene | 0.16 | 0.00 | 0.16 | 0.00 |
| | Antimony | 0.14 | 0.02 | 0.12 | 0.00 |
| | Cadmium | 0.13 | 0.01 | 0.11 | 0.00 |
| | Dioxins | 0.10 | 0.01 | 0.10 | 0.00 |

| | EDIP Human Toxicity in Soil | Process Contribution % | | | |
|---|---|---|---|---|---|
| | Substance | **Total** | **Transport** | **Electricity** | **Heat** |
| Substance Contribution % with 0.1% cut off | Total of all compartments | 100.00 | 7.77 | 90.97 | 1.26 |
| | Remaining substances | 0.93 | 0.18 | 0.75 | 0.01 |
| | Benzene | 62.32 | 0.55 | 61.76 | 0.01 |
| | Benzene | 11.89 | 2.67 | 8.05 | 1.17 |
| | Iron | 9.81 | 0.66 | 9.14 | 0.00 |
| | Mercury | 2.65 | 0.06 | 2.59 | 0.00 |
| | Benzene | 2.36 | 1.43 | 0.93 | 0.00 |
| | Iron | 2.26 | 1.13 | 1.08 | 0.06 |
| | Aluminum | 1.92 | 0.03 | 1.89 | 0.00 |
| | Iron | 1.27 | 0.03 | 1.24 | 0.00 |
| | Benzene | 0.87 | 0.41 | 0.46 | 0.00 |
| | Benzene | 0.74 | 0.16 | 0.57 | 0.00 |
| | Arsenic | 0.65 | 0.05 | 0.60 | 0.00 |
| | Manganese | 0.59 | 0.00 | 0.59 | 0.00 |
| | Mercury | 0.50 | 0.29 | 0.20 | 0.00 |
| | Vanadium | 0.38 | 0.03 | 0.35 | 0.00 |
| | Fluoride | 0.34 | 0.00 | 0.33 | 0.00 |
| | Iron | 0.14 | 0.01 | 0.14 | 0.00 |
| | Mercury | 0.14 | 0.05 | 0.09 | 0.00 |
| | Chromium | 0.12 | 0.01 | 0.11 | 0.00 |
| | Antimony | 0.12 | 0.01 | 0.11 | 0.00 |

**Table 5. 13: Human Toxicity Impact in Mechanical Recycling: Process contribution, substance contribution and characterisation factors for both CML and EDIP (Air, Water and Soil) methods. Data reported with various cut-off levels and reported as % of total value**

LCIA methods comparison at midpoint level (CML vs. EDIP) could be summarised as below:

- Avoided burden played a significant role in improving the environmental profile recycling scenarios, particularly on mechanical recycling. However, the assumption of a 1:1 substitution ratio of recycled plastic replacing virgin plastic will not be possible considering the reliability and quality of the waste plastic source. The effect of the substitution ratio on an environment profile was evaluated and presented in Figure 5.13. When evaluated through Eco-indicator-99 single score, a recycled to virgin substitution ratio of 1:0.10-0. was found to be sufficient enough to make better environmental credentials to justify mechanical recycling over incineration with energy recovery. In other words, atleast 10-15% of virgin plastics to be replaced by recycled plastics to enable mechanical recycling environmentally better than incineration with energy recovery. The substitution ratio moved towards to 1: 0.35-0.40 when evaluated through resource depletion as the basis of comparison. The breakeven point evaluation is shown in figure 5.13. In other words, atleast 35 to 40% of virgin plastics to be replaced by recycled plastics to enable mechanical recycling be environmentally better than incineration with energy recovery when we consider resource depletion alone. This concedes with industrial practices where 5-10% of in-house scrap is recycled which provides both environmental and economic benefits. This cross-over point to be evaluated case by case basis as factors such as efficiency of recycling operation, amount of losses in material recovery process, types of materials recovered, transport distances, end use application, energy recovered from incineration process and LCI of virgin polymer will play a significant role in determining the outcome.

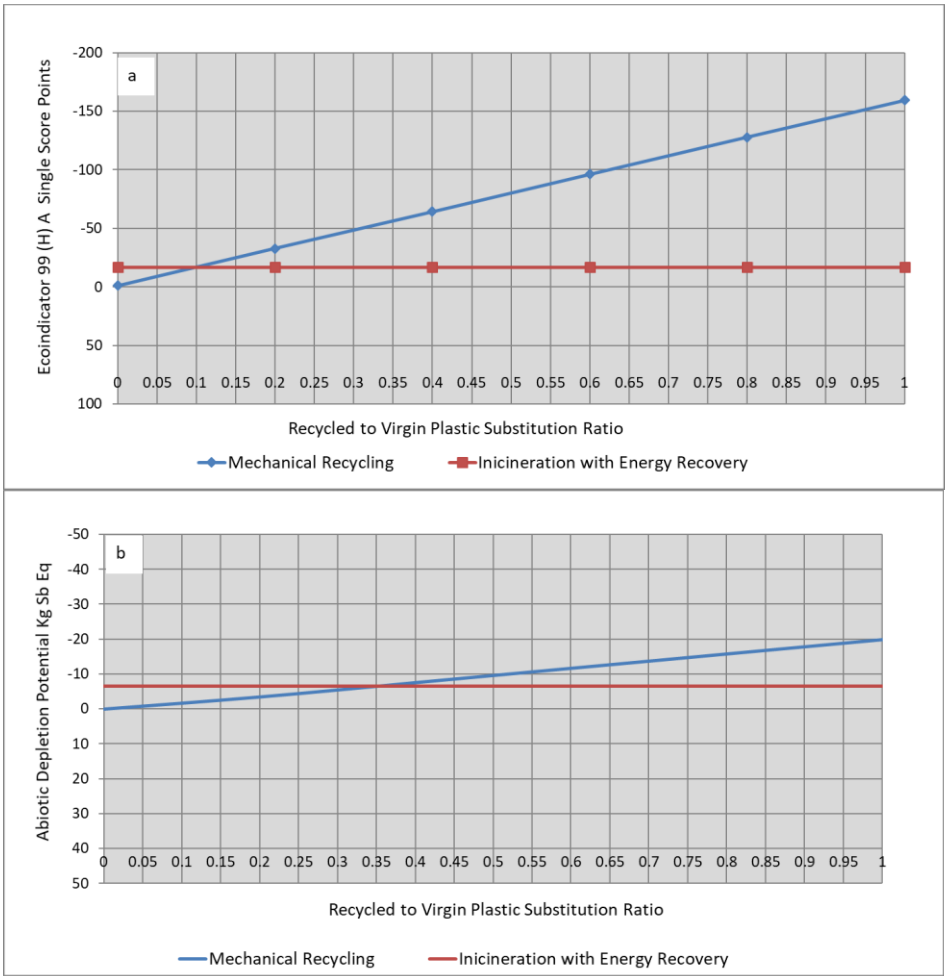


**Figure 5. 13: Recycled to Virgin plastics substitution ratio estimation with Eco-indicator 99 (a) and Abiotic resource depletion (b). Incineration with energy recovery is used as the baseline of comparison in both the cases.**

- Some of the impact categories are similar to each other with minor differences in characterisation factors (global warming, acidification and ozone layer depletion).
- Some of the impact categories comparisons are not straightforward owing to their background mechanisms, rationales and purposes.
- Process contribution was found to be the same in most of the impact categories, irrespective of the method.
- Substance contribution was found to be dissimilar reflecting the purpose of measurement.
- The EDIP method was found to be more site-specific allowing to impart site specific impact category. For instance, human toxicity is one indicator in the CML method whereas it is a multiple indicator in EDIP.

### 5.7.2 Comparison of single score results

LCA single score results from the following methodology will be compared and discussed in this section:

- Eco-Indicator Hierarchist Method
- Eco-Indicator Egalitarian Method
- Eco-Indicator Individualist Method
- EDIP 2003 Method
- Cumulative Energy Demand (CED) Method

As shown in Figure 5.9, all LCIA methods mentioned above, except EDIP 2003, favour mechanical recycling. Another common observation among all of these results is the negative single score, except in the EDIP method, in both mechanical recycling and incineration with energy recovery indicating the significance of avoided burden which completely outweighs the impact generated through mechanical recycling and incineration. The EDIP method did not include resources in single score resulting in losing the advantage of resource gained from avoided burden, which played a significant role in the resulting reverse outcome in EDIP when compared with Eco-indicator and CML methods.

For the purpose of comparison of methods, 'Avoided Burden' is excluded and the results are reported in Figure 5.14. It is interesting to see contradictory outcomes between Figures 5.9 & 5.14 and the role of the LCIA method in influencing the LCA outcome. Excluding avoided burden from LCA models favoured plastics incineration – except in Eco-indicator 99 H/I/E methods.

The reason behind this shift in outcome will be examined through contribution analysis. The contributing factors behind the Eco-indicator results are shown in Figure 5.15, with results before and after aggregation. The main contributors towards mechanical recycling impacts are fossil fuels, respiratory inorganics and climate change in Eco-indicator 99 Hierarchist and Egalitarian approaches, whereas climate change, respiratory inorganics and minerals are the main contributors in the Individualist approach. This difference is because no fossil fuel indicator is available in the Eco-indicator individualist approach. This could be seen in the aggregated results where resource contribution is less in the Individualist approach when compared against the Hierarchist and Egalitarian approaches. Climate change, fossil fuels and respiratory inorganics all contribute towards higher single scores in incineration and are mainly from emissions given off from the incineration process, whereas contributions in mechanical recycling are predominantly from energy usage and transport.

Single score EDIP-2003 results with breakdown (excluding avoided burden) are shown in Figure 5.16. A contribution analysis indicates that radioactive waste from power usage and eutrophication from recycling effluent treatment are the top contributors leading to a higher score of mechanical recycling. Carbon emissions from incineration gases and radioactive waste from electricity generation are contributors in plastics incineration. As mentioned in the inventory table, the processing of 1000kg of plastics waste needs 724 KWH of electricity and 68 MJ of heat, whereas the incineration of 1000kg of plastics needs 171KHW of electricity and 724 MJ of heat which explains the higher score of mechanical recycling. Similar results were observed in cumulative energy demand (CED) as shown in Figure 5.17. Over 90% of the contribution is from non-renewable fossil fuels and non-renewable nuclear from energy and gas usage in both mechanical recycling and energy recovery and, hence, the lower-energy-intensive process, plastics incineration, is favoured in the CED LCIA method.

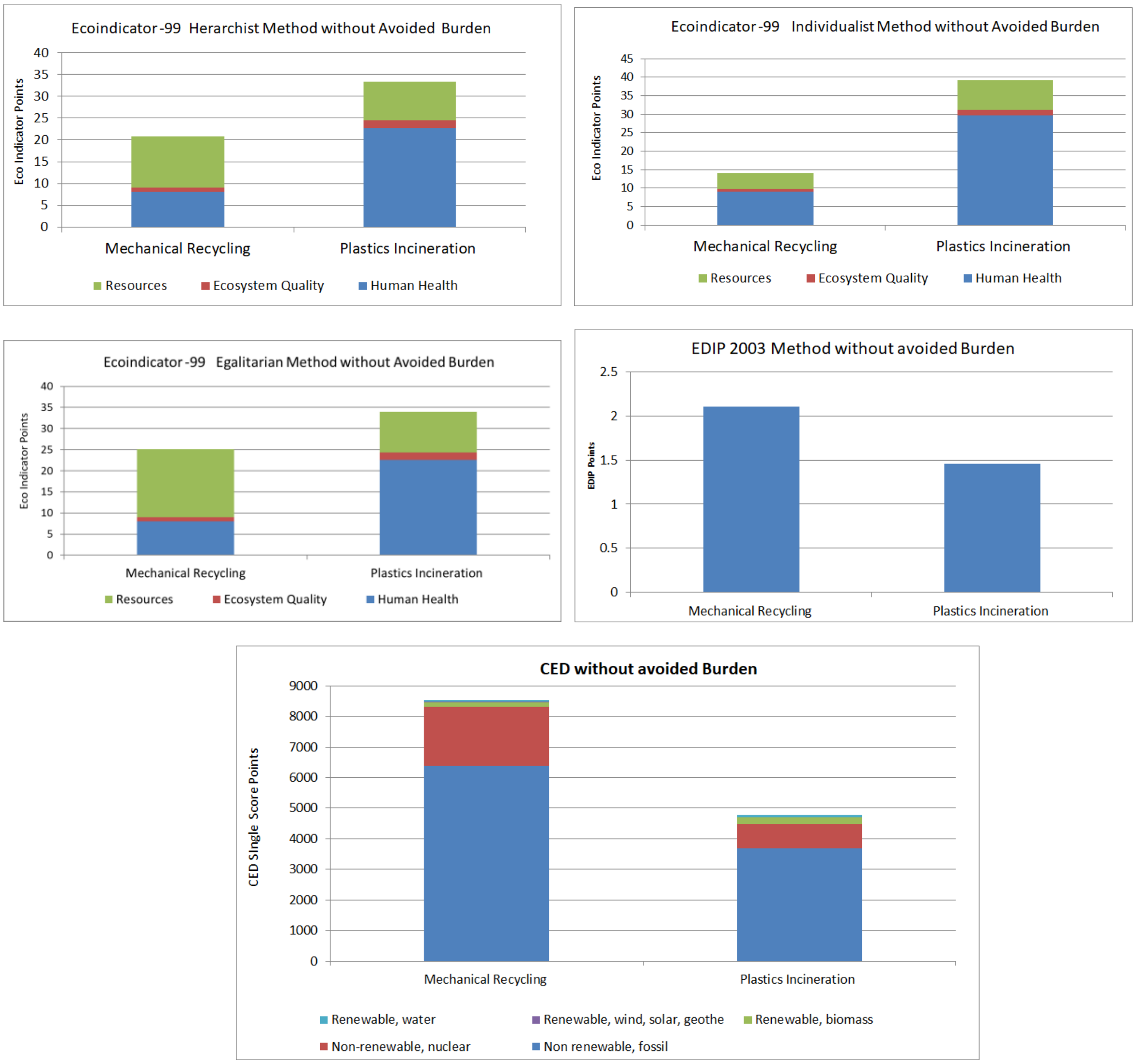


**Figure 5. 14: Single score LCA results (excluding avoided Burden) of Mechanical Recycling and Plastics Incineration through various LCIA results**

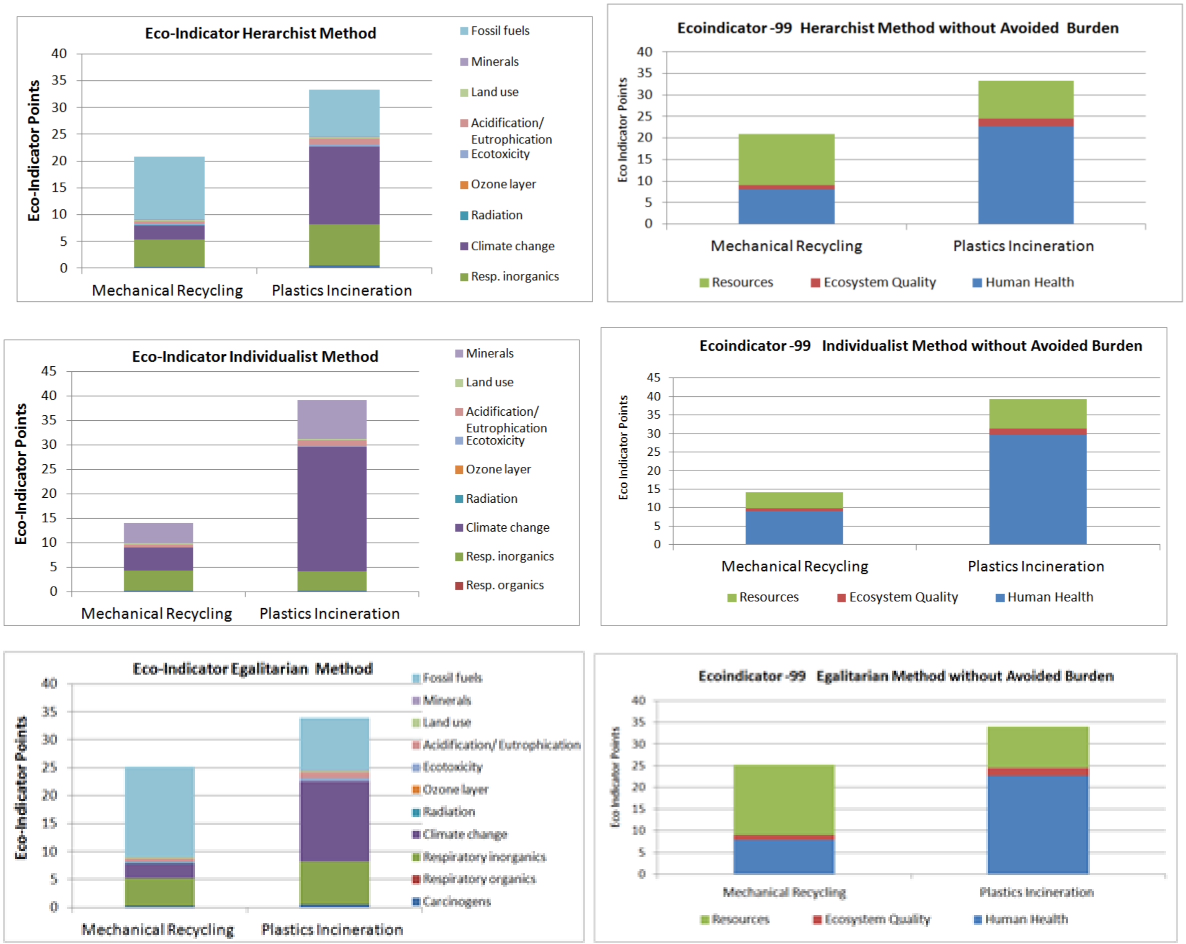


**Figure 5. 15: Contribution analysis of Eco-Indicator Results showing individual impact categories in left and aggregated results in right. All values are excluding avoided burden**

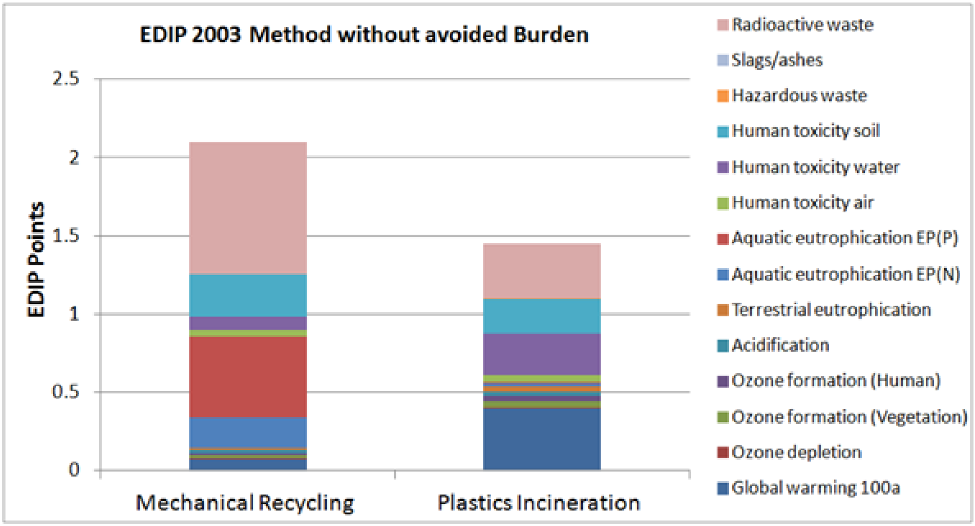


**Figure 5. 16: Contribution Analysis of single score EDIP 2003 results**

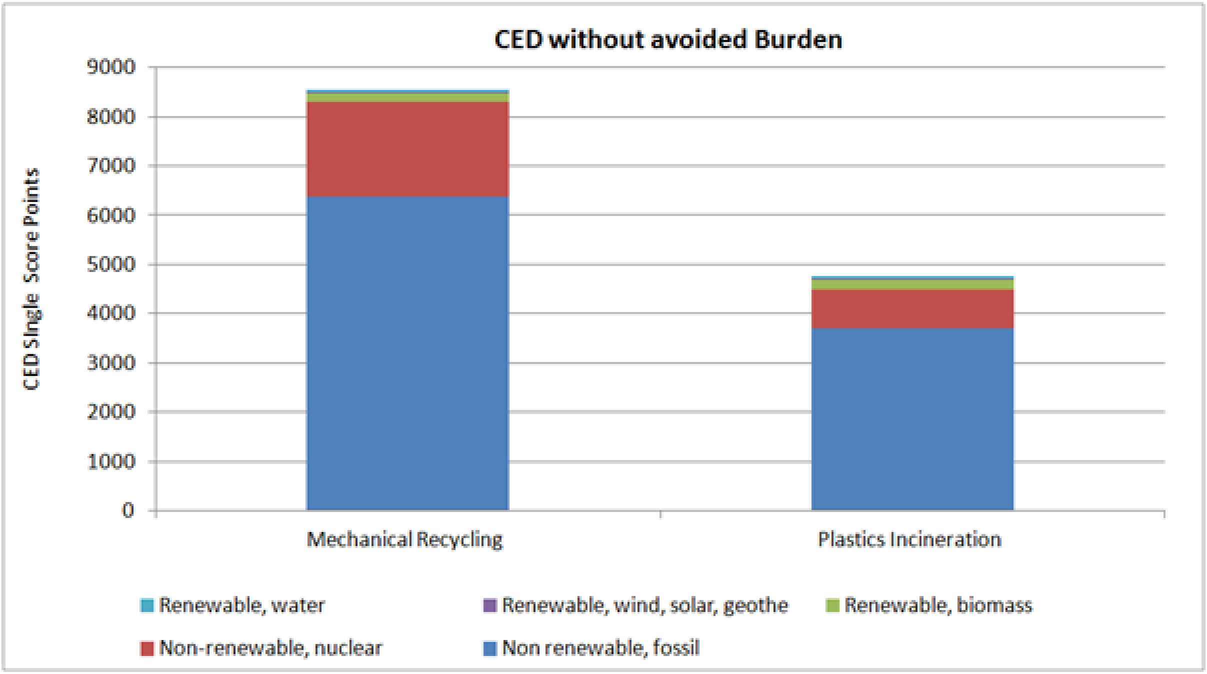


Figure 5. 17: Contribution Analysis of single score Cumulative Energy Demand (CED)

## 5.8 Conclusion

An LCA study was conducted comparing mechanical recycling and energy recovery with various impact assessment methods. Avoided Burden or Environmental Credit played a significant role in masking the environmental impacts of both recycling and energy recovery. Both the options, mechanical recycling and energy recovery, seem to be having positive environmental benefits when considering the benefits generated from the resulting product from EOL operation. When comparing the benefits in both the CML and EDIP scenarios, the environmental benefit from mechanical recycling seems significantly higher than incineration with energy recovery. This is mainly because of an assumption that recycled plastics are replacing virgin plastics in a 1:1 ratio, which is an optimistic assumption, however, convincing evidence is not provided. The recycled plastic to virgin plastic substitution ratio evaluated through an eco-indicator and an abiotic depletion potential indicator shows that around 1: ~ 0.1 to 0.5 is sufficient to demonstrate positive environmental credentials. However, this depends on factors, such as: material loss in material recovery operations, energy usage in recycling operations, energy recovery efficiency, material properties, and end-use requirement.

A comparison between CML and EDIP methods indicates that most of the indicators have given similar outcomes when comparing mechanical recycling and incineration – except ‘resources’ which is purely because of different mechanisms of calculation. The comparison of eco-toxicity and human toxicity indicators were not straightforward owing to their difference in units, calculation methods and number of indicators. However, it is interesting to note that the contribution factors are different among these indicators. This difference in contribution factors was also reported in Photochemical oxidants and resource usage. The complexity of different calculation mechanisms and units were addressed, and a comparison was established through process contribution, substance contribution and characterisation factors. One of the common contributors to most of the impacts in mechanical recycling is that of electricity usage. One of the advantages of a detailed impact assessment is the identification of ‘hot spots’ and impact reduction strategies could be applied to make the process more environmentally friendly. For instance, NatureWorks (one of the polylactic acid manufacturers) used renewable energy to replace 50% of fossil energy which resulted in an 85% reduction of carbon emissions and a 50% reduction in fossil energy (249). Apart from the decrease of carbon emissions and resource consumption, other related impacts such as toxicity emissions related to energy generation would potentially decrease with the use of clean and renewable energy.

The LCIA method seems to show a clear effect between Eco-Indicator-99, EDIP-2003 and CED single score results. Eco-inidcator-99 and CED method favoured mechanical recycling whereas EDIP 2003 is in favour of incineration. This is mainly due to resource consumption not contributing significantly enough in EDIP and CED owing to its calculation mechanism.

# Chapter 6: Conclusion

The durability of polymers, along with their increased usage, created serious waste management issues with plastic waste. One of the latest studies indicates that, out of total plastics produced between 1950 to 2015 (8300 million tons), only 21% is recycled or incinerated and the remaining 6300 million tons (approx..) has ended-up in landfill or the natural environment including ecosystems, water streams and oceans (15). This fate of plastics ending-up in eco-systems is of serious concern to our entire society, affecting all forms of life including both wildlife and human. One of the recent estimates predicts that at least 5 trillion plastic pieces, in total weighing over 250,000 tons are floating on the seas (250). Over 260 species have been reported to have been affected by plastic pollution, via ingestion or entanglement, this is affecting their routine activities (feeding and movement) leading to reduced reproduction, serious bodily damage, and death. Some of the toxic chemicals and additives contained in plastic waste are sources of potential health risks causing cancer and reproductive abnormalities (9).

Conversely, waste plastics are source of energy (with high calorific value over 40MJ per kg) and are a potential high value renewable resource which could displace materials from fossil fuels. Utilising plastic waste in various combinations can pave the way to a circular economy which is the current technological and political target for many countries. Successful management of plastic waste has advantages and some of the critical benefits are as follows:

- Protect ecosystems and natural habitats
- Protect wildlife, sea life and human health
- Decrease of littering and rubbish accumulation in natural environment
- Decrease in global warming gases
- Decrease in fossil fuel consumption
- Development and use of environmentally sustainable products and process
- Establishment of permanent circular economy
- Complement economic growth
- Job creation

A Life Cycle Assessment (LCA) tool has great potential to support scientists and engineers to achieve most of the above benefits, if not all. In this research, the potential of LCA has been demonstrated to support the Sustainable Product Development Process in the Plastics Recycling sector along with addressing some its challenges. The complexity of the plastic waste management process can be understood from the literature review chapter (Chapter 2). Complexity is because of direct and indirect technological, environmental & commercial technicalities. Along with this, numerous challenges are involved in plastic waste management and recycled plastic product development processes where LCA is used as a bridge and a platform to interlink and analyse to come-up with synergistic sustainable solutions suitable for our society. Some of the technicalities and challenges presented in **Chapter 1 and 2** are presented below:

- Multitude of waste management choices available to manage plastic waste along with their environmental profiles. Commercial exploitations are included wherever available
- Environmental concern of plastic waste incineration emissions and its benefit through energy recovery
- Development of plastic products from mixed plastic waste which are bound to have poor properties
- Challenges in life cycle impact assessment methods
- Environmental profile of various products developed from plastic waste through feedstock recycling and incineration

**Chapter 3** analysed two potential opportunities, covering both technical and environmental challenges, of utilising recycled plastic composites in automotive and civil & infrastructural applications. The purpose of choosing the construction and automotive markets was based on commercial strategy as these markets are ranked as the second and third largest consumer (165) of plastic products covering around one-third of the total plastics market in Europe. These applications will enable mass utilisation of plastic waste and have great potential to increase plastic waste consumption near to the plastic waste generation rate. Polymer-based products in the automotive and construction sector are of different types and specifications which will provide various choices and opportunities for plastic waste where it could be utilised based on its strength rather than based on its limitations.

Fibre materials were chosen as a reinforcement as these provide a significant improvement in mechanical properties. Mechanical properties of composites were predicted through micro-mechanical models. Life Cycle Inventory (LCI) of recycled plastics and flax fibres were adapted from peer-reviewed literature. The life cycle of the product was modelled to predict environmental impacts. Relations between environmental impact and mechanical properties were established. Life Cycle Impact

Assessment (LCIA) was carried out through both CML and Eco-Indicator methodology. LCA results indicate recycled plastic composites have clear environmental advantages in civil / infrastructural applications when compared to the virgin alternative. LCA results from the analysis of automotive applications were not straightforward; clear environmental benefits were not demonstrated. The best-case scenario indicates that environmental performance will be similar to that of virgin plastic composites. However, lightweight reinforcement (flax fibre) could be utilised with recycled plastic when replacing virgin plastic containing glass fibre to achieve a lower environmental burden. Further work on flax fiber composites, particularly, on moisture absorption, service life and ageing would be required.

**Chapter 4** analysed the environmental impact of mixed plastic waste replacing softwood lumber. Replacing wooden products in civil engineering applications has great potential to consume large quantities of plastic waste. Wood is a structural material used in demanding applications and replacing wooden products with a recycled plastic product is a classical demonstration of 'Upcycling of Plastic wastes' where recycled plastics are valued as high-performance material. The comparison of wooden and recycled plastic products in lumber applications is an interesting study as their upstream processes are not similar and compete against nature with their advantages. Wooden products are from a forest, which is a proven carbon store, whereas recycled products are from waste which is a renewable resource.

A life cycle inventory of softwood lumber was based on data from peer reviewed literature covering plantation, roundwood conversion, drying, sawing, planing and treatment. The carbon neutrality of the wooden product is taken into account. The information for recycled plastic lumber was obtained from a confidential moulding process. Wooden and unreinforced recycled plastic lumber were analysed through individual CML impact categories and overall weighed and grouped eco-indicator single-score. Mixed results were obtained when individual impact categories were considered. The critical impact category, GWP, favoured wooden lumber, as carbon sequestration played a significant role in reducing the $CO_2$ footprint of the product. However, the eco-indicator single-score favoured recycled plastic lumber. Incineration with energy recovery was found to have provided a significant boost in improving the environmental profile of recycled plastic as it has a high energy content and replacing energy and heat from fossil resources had strong environmental benefits. However, addition of reinforcements to recycled plastics and importing of softwood lumber found to increase the environmental impact which are addressed through sensitivity analysis.

The context of **Chapter 5** is in a slightly different genre than Chapter 3 and 4. Two plastic waste management scenarios, mechanical recycling (MR) and incineration with energy recovery (ER), were chosen for comparison purposes with LCIA methods as this is important to a product development engineer who is involved in recycled plastic product development. The life cycle inventory (LCI) of mechanical recycling and energy recovery are adapted from peer-reviewed literature. Two mid-point methods (CML vs. EDIP 2003) and three end-point single score LCIA methods (Eco-Indicator-(H), EI-(I), EI-(E), EDIP 2003 and CED) were compared to see the effect of LCIA methods on comparison outcome. The differences in methodology were identified.

The comparison of MR and ER scenarios indicate that avoided burden was found to have played a significant role in influencing the comparison outcome. Particularly, assumption of the recycled plastic product replacing virgin plastic in a 1:1 substitution ratio is addressed through breakeven point to impart quality of the recycled product in LCA. Hence, analysis was carried out by excluding avoided burden in both the scenarios. CML vs. EDIP 2003 indicate that resources and toxicity are the main differences. Resources in EDIP is just a summation of all resources whereas CML used reference substance to include depletion quantity and depletion rate. CML and EDIP used different units which made comparison challenging. However, substance and process contribution techniques were adapted to address the differences in toxicity measurement. In single-score LCIA methods, Eco-indicator and CED favoured MR, whereas CED favoured ER. This is because of less-intensive accounting of resource use in the EDIP and CED methods. This chapter indirectly insists the requirement of international standard on LCA of plastics recycling to standardize data collection procedure, LCI, LCIA, number of impact indicators, types of single scores and recommendations on using avoided burden. Standardization will play a significant role in simplifying LCA studies which will promote comparability and adaptability of unit processes on various LCA studies.

Developing a sustainable application for recycled plastics needs the participation of members from raw material manufacturing, reprocessors, OEMs, local councils, environmental agencies, material recovery facilities (MRF) and research institutions. Presence of full-scale consortium would have complemented this project along with positive commercial impact.

Based on above summary, technical contribution to the field of Polymer Recycling and LCA are as follows:

- Demonstrated the LCA study on composites developed from recycled polymers.
- The environmental profiles of composites from recycled polymers were evaluated for two potential markets & applications: the automotive and construction industries. This concept could be exploited by both academia and industrial sectors involved in the field of material recycling to develop and commercialise various recycled materials in the above and new market segments.
- Direct correlation between mechanical performance and environmental profile of two types of reinforcements (glass fibre and flax fibre) for recycled polymers were evaluated and reported. This direct correlation between mechanical performance and environmental profile could be expanded to various recycled polymers (PET, PBT, Nylon etc) along with various fillers & reinforcements (mica, talc, calcium carbonate) to develop material library. Material library (similar to Ashby plot) and supply chain data could potentially revolutionise the applications of recycled polymers and will strongly promote consumption of recycled polymers.
- Materials of unique environmental profiles: recycled plastic lumber and wooden lumber were compared and analysed as it is one of the commercially exploited applications. This will provide designer engineers to choose appropriate material & formulation for a chosen application.
- Challenges in LCIA are explained and role of the LCIA method on project outcome was demonstrated along with underlying challenges by comparing two waste management scenarios. This study will provide insights to LCA analyst on impact of various LCIA methods.

This study will assist product development engineers, polymer scientists, environmental analysts and business development executives to understand how Manufacturing Technology, Materials Chemistry, Sustainability / Environmental Impacts and Commercial Application are interlinked with each other. This research has demonstrated the application of the Life Cycle Assessment in developing sustainable solutions to plastic waste which is playing a critical role in our society.

## Recommendation for future research

1. **Finite Element Analysis (FEA):** FEA could be utilised in the material development phase to reverse engineer material requirements or specification for any new applications where recycled plastic could be used. This will help in identifying plastic waste sources or composition

(i.e recycled polymers from packaging waste, electrical and electronic waste and automotive shredder residue etc.). This will also enable us to incorporate design modification to accommodate limitations of recycled products (example: ribs or treads through metallic inserts)

2. **Reinforcements from wastes:** Most of the material manufacturing process will generate process scraps. Depending on the type of scraps, there is a possibility that scraps could be a reinforcement to plastic wastes. Some of the example scraps are: material of different particle sizes in the mica or talc industry, start-up or shut down scraps in the glass fibre or glass flake industry. These scraps do not have any economic value but they could still retain reinforce-ability. These materials also do not have any environmental burden. If successful, recycled plastic composite material will have a unique technical, economical and environmental profile with lots of chances to attain commercial success.

3. **Self-Reinforced Plastics (SRP):** Careful selection of plastic waste composition has a potential to develop SRP composite made of mixed plastics waste. This could be attained through fibre spinning or stretching of sorted plastic waste and utilizing oriented polymer as a reinforcement to recycled polymer matrix. SRP has unique applications in sports engineering and automotive markets.

4. **Accurate estimation of environmental impacts of plastics:** Plastic wastes littering is a serious concern to our society and reported to have caused permanent damage to our society. This damage has to be quantified and incorporated in life cycle models of products with single use applications. Successful collection and processing of plastic wastes mitigates the impacts associated with littering. This impact mitigation should be incorporated as an environmental credit in life cycle models which are based on plastic waste recovery and collection.

5. **Effect of various functional units:** Chapter 4 focussed on volume ($1m^3$) as a functional unit. Effect of other units of comparison like number of lumbers structures of same dimensions, lumber materials with same mechanical properties will provide further insights to the environmental performance.

6. **LCIA methods:** This LCA study could be taken further by advanced LCIA methods such as ReCiPe and EIOA (Economic input-output analysis) to overcome limited LCI availability, more substance coverage broad range of mid-point indicators, robust endpoints, and to reduce uncertainties.

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# Chapter 8: Appendices

## 8.1 Appendix 1

Flax Fibre Production Mass Balance Sheet (173)

| Input | kg | | Output | kg |
|---|---|---|---|---|
| **Plant Growing** | | | | |
| Seed | 19.8 | | Dry Green Flax stems | 6000 |
| | | | | |
| **Warm Water Retting** | | | | |
| Dry Green Flax stems | 6000 | | Dry Retted Flax | 5400 |
| | | | | |
| **Scutching** | | | | |
| Dry Retted Flax | 5400.00 | | Scutched Long Fibre | 972 |
| | | | Scutching Tow | 3528.36 |
| | | | Shives | 3834 |
| | | | | |
| **Hackling** | | | | |
| Scutched Long Fibre | 972.0 | | Sliver | 637.632 |
| | | | Hackling Tow - Short Fibre | 243.2916 |
| | | | | |
| **Roving** | | | | |
| Sliver | 637.63 | | Rove | 605.7504 |
| | | | | |
| **Bleaching** | | | | |
| Rove | 605.75 | | Bleached Rove | 539.1179 |
| | | | | |
| **Spinning** | | | | |
| Bleached Rove | 539.12 | | Yarn in Cops | 517.5531 |
| | | | | |
| **Winding** | | | | |
| Yarn in Cops | 517.55 | | Yarns in Cones | 517.5531 |

## 8.2 Appendix 2

Raw data used in Figure 3.7 and 3.8 – LCIA results through CML methodology

| **All Impact Categories** | | 25% GF - VPP | | | 25% GF - RPP | | |
|---|---|---|---|---|---|---|---|
| Impact category | Unit | Raw Material | EOL | Total | Raw Material | EOL | Total |
| Abiotic depletion | kg Sb eq | 2.4E-02 | -3.8E-03 | 2.0E-02 | 1.3E-02 | -3.8E-03 | 8.8E-03 |
| Acidification | kg SO2 eq | 1.2E-02 | -1.2E-03 | 1.1E-02 | 1.0E-02 | -1.2E-03 | 9.1E-03 |
| Eutrophication | kg PO4--- eq | 9.7E-04 | -7.0E-05 | 9.0E-04 | 7.7E-04 | -7.0E-05 | 7.0E-04 |
| Global warming (GWP100) | kg CO2 eq | 2.4E+00 | 6.7E-01 | 3.1E+00 | 1.7E+00 | 6.7E-01 | 2.4E+00 |
| Ozone layer depletion (ODP) | kg CFC-11 eq | 1.3E-07 | -2.4E-08 | 1.1E-07 | 1.3E-07 | -2.4E-08 | 1.1E-07 |
| Human toxicity | kg 1,4-DB eq | 5.8E+00 | 3.1E+07 | 3.1E+07 | 5.7E+00 | 3.1E+07 | 3.1E+07 |
| Fresh water aquatic ecotox. | kg 1,4-DB eq | 1.1E-02 | 4.7E-03 | 1.6E-02 | 1.1E-02 | 4.7E-03 | 1.6E-02 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 5.0E+01 | 6.0E+00 | 5.6E+01 | 5.0E+01 | 6.0E+00 | 5.6E+01 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 2.5E-02 | -2.7E-04 | 2.4E-02 | 2.5E-02 | -2.7E-04 | 2.5E-02 |
| Photochemical oxidation | kg C2H4 | 5.2E-04 | -5.2E-05 | 4.7E-04 | 3.8E-04 | -5.2E-05 | 3.3E-04 |

| **All Impact Categories** | | 25% FF - VPP | | | 25% FF - RPP | | |
|---|---|---|---|---|---|---|---|
| Impact category | Unit | Raw Material | EOL | Total | Raw Material | EOL | Total |
| Abiotic depletion | kg Sb eq | 2.62E-02 | -2.16E-02 | 4.59E-03 | 7.00E-03 | -2.16E-02 | -1.46E-02 |
| Acidification | kg SO2 eq | 9.83E-03 | -6.99E-03 | 2.84E-03 | 6.22E-03 | -6.99E-03 | -7.70E-04 |
| Eutrophication | kg PO4--- eq | 3.03E-01 | -4.69E-04 | 3.02E-01 | 3.03E-01 | -4.69E-04 | 3.02E-01 |
| Global warming (GWP100) | kg CO2 eq | 2.64E+00 | -7.79E-01 | 1.86E+00 | 1.49E+00 | -7.79E-01 | 7.13E-01 |
| Ozone layer depletion (ODP) | kg CFC-11 eq | 9.13E-08 | -1.49E-07 | -5.78E-08 | 9.21E-08 | -1.49E-07 | -5.70E-08 |
| Human toxicity | kg 1,4-DB eq | 1.19E-01 | 5.34E+07 | 5.34E+07 | 1.07E-01 | 5.34E+07 | 5.34E+07 |
| Fresh water aquatic ecotox. | kg 1,4-DB eq | 2.54E-02 | 4.94E-03 | 3.04E-02 | 2.60E-02 | 4.94E-03 | 3.10E-02 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 4.69E+01 | -1.10E+01 | 3.59E+01 | 4.60E+01 | -1.10E+01 | 3.50E+01 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 2.96E-03 | -1.85E-03 | 1.11E-03 | 3.51E-03 | -1.85E-03 | 1.66E-03 |
| Photochemical oxidation | kg C2H4 | 4.37E-04 | -3.35E-04 | 1.02E-04 | 1.91E-04 | -3.35E-04 | -1.45E-04 |

# 8.3. Appendix 3

## A) Degree of light weighting and fuel reduction value calculation

**Degree of Lightweighting and FRV Calculation**

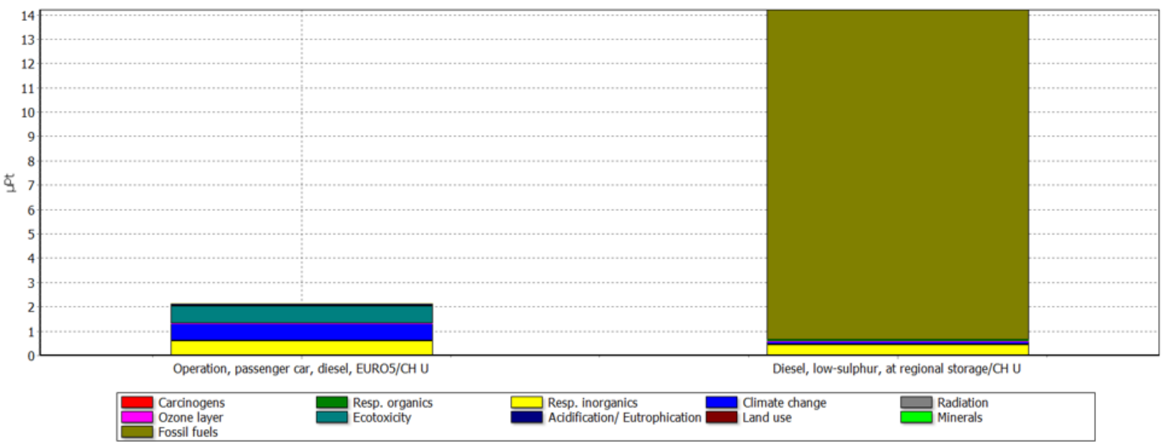
| Material | Fiber Volume Fraction $V_f$ | Youngs Modulus E GPa | Composite Density ρ | Material Index | Degree of Light Weighting % | Weight Saving kg | FRV[1] (Fuel Savings) in kg | Average FRV[1] kg | Std. Dev |
|---|---|---|---|---|---|---|---|---|---|
| Steel | NA | 210 | 7.8 | 0.76 | NA | NA | NA | NA | NA |
| VPP - GF | 25% | 7.9 | 2.01 | 0.99 | 23.2 | 25.6 | 38.24 | 38.24 | NA |
| VPP - FF Upper Bound | 25% | 7.7 | 1.19 | 1.66 | 54.1 | 59.8 | 89.31 | 85.8 | 3.5 |
| VPP - FF Lower Bound | 25% | 5.9 | 1.19 | 1.52 | 49.9 | 55.1 | 82.29 | | |
| RPP-GF Upper Bound | 25% | 7.9 | 2.01 | 0.99 | 23.2 | 25.6 | 38.24 | 36.7 | 1.6 |
| RPP-GF Lower Bound | 25% | 7.34 | 2.01 | 0.97 | 21.3 | 23.5 | 35.10 | | |
| RPP-FF Upper Bound | 25% | 7.72 | 1.19 | 1.66 | 54.2 | 59.8 | 89.37 | 84.5 | 4.9 |
| RPP-FF Lower Bound | 25% | 5.35 | 1.19 | 1.47 | 48.2 | 53.2 | 79.55 | | |

* Weight savings calculated were calculated based on degree of light weighting with respect to the weight of metalic component which is 110kg.

1 - indicates fuel reduction value

## B) Average data for the operation of a newly registered Euro5 car (166)

Passenger Car LCA model for driving 1km. Analysed through Eco-indicator Model Single score method. As shown below diesel contributes around 87% of environmental impact during use-phase of the car



Analysing 1 m 'Operation, passenger car, diesel, EURO5/CH U';
Method: Eco-indicator 99 (H) V2.05 / Europe EI 99 H/H / Single score / Excluding infrastructure processes / Excluding long-term emissions

# 8.4 Appendix 4

Mid-point Impact assessment results raw data

| CML 2 Baseline 2000 LCIA Method (Inclusive of Avoided Burden) | | | |
|---|---|---|---|
| **Impact category** | **Unit** | **Mechanical Recycling** | **Plastics Incineration with energy recovery** |
| Abiotic depletion | kg Sb eq | 🟩 -19.76 | -6.42 |
| Acidification | kg SO2 eq | 🟩 -2.65 | -0.27 |
| Eutrophication | kg PO4--- | 126.13 | 🟩 0.08 |
| Global warming (GWP100) | kg CO2 eq | 🟩 -1.05E+03 | 1.58E+03 |
| Ozone layer depletion (ODP) | kg CFC-11 | 🟩 -2.60E-05 | -1.17E-05 |
| Human toxicity | kg 1,4-DB | -12.88 | 🟩 -81.69 |
| Fresh water aquatic ecotox. | kg 1,4-DB | 🟩 -6.19 | -5.08 |
| Marine aquatic ecotoxicity | kg 1,4-DB | 20282.06 | 🟩 -62136.50 |
| Terrestrial ecotoxicity | kg 1,4-DB | 1.23 | 🟩 -0.20 |
| Photochemical oxidation | kg C2H4 | 🟩 -0.34 | -0.03 |
| 🟩 | Green Indicates lowest environmetal burden | | |

| EDIP 2003 LCIA Method (Inclusive of Avoided Burden) | | | |
|---|---|---|---|
| **Impact category** | **Unit** | **Mechanical Recycling (MR19)** | **Plastics Incineration MSWI19** |
| Global warming 100a | kg CO2 eq | 🟩 -1044.45 | 1576.85 |
| Ozone depletion | kg CFC11 eq | 🟩 0.00 | 0.00 |
| Ozone formation (Vegetation) | m2.ppm.h | 🟩 -7912.15 | 529.57 |
| Ozone formation (Human) | person.ppm.h | 🟩 -0.61 | 0.03 |
| Acidification | m2 | 🟩 -41.68 | 2.60 |
| Terrestrial eutrophication | m2 | 🟩 -32.27 | 17.12 |
| Aquatic eutrophication EP(N) | kg N | 1.75 | 🟩 0.06 |
| Aquatic eutrophication EP(P) | kg P | 1.68E-01 | 🟩 -1.57E-04 |
| Human toxicity air | m3 | 🟩 -5488342.70 | -1547375.80 |
| Human toxicity water | m3 | 🟩 -3598.15 | 3118.02 |
| Human toxicity soil | m3 | -0.17 | 🟩 -53.03 |
| Ecotoxicity water chronic | m3 | 🟩 -23644.89 | -13955.22 |
| Ecotoxicity water acute | m3 | -6489.28 | 🟩 -6885.71 |
| Ecotoxicity soil chronic | m3 | -0.51 | 🟩 -50.11 |
| Hazardous waste | kg | 🟩 -3.07 | 0.09 |
| Slags/ashes | kg | 🟩 -0.29 | 0.00 |
| Bulk waste | kg | 🟩 -3.64 | 1.39 |
| Radioactive waste | kg | 0.03 | 🟩 -0.03 |
| Resources (all) | kg | 🟩 -0.04 | 0.00 |
| 🟩 | Green Indicates lowest environmetal burden | | |

# Publications

## Journal Publications

- S Rajendran, A Hodzic, C Soutis & M Al-Maadeed (2012) Review of life cycle assessment on polyolefins and related materials, Plastics, Rubber and Composites, 41:4-5, 159-168, DOI: 10.1179/1743289811Y.0000000051
- S Rajendran, L Scelsi, A Hodzic, C Soutis, M Al-Maadeed (2012) Environmental impact assessment of composites containing recycled plastics, Resources, Conservation and Recycling, 60, 131-139, DOI: 10.1016/j.resconrec.2011.11.006
- S Rajendran, A Hodzic, L Scelsi, S Hayes, C Soutis, M AlMa'adeed & R Kahraman (2013) Plastics recycling: insights into life cycle impact assessment methods, Plastics, Rubber and Composites, 42:1, 1-10, DOI: 10.1179/1743289812Y.0000000002

## Conference Proceedings

- S. Rajendran, A Hodzic, C Soutis, S Hayes, M Al-Maadeed "Composites Product Development – Sustainability Approach" in 10th Annual Conference: Innovation in composites, "Composites UK" on 5th-6th May 2010
- S. Rajendran, A Hodzic, C Soutis, S Hayes, M Al-Maadeed, The life cycle assessment on plastics recycling, 2010 June 6th -10th, ECCM 14, Budapest, Hungary
- S. Rajendran, A Hodzic, C Soutis, S Hayes, M Al-Maadeed, Environmental impact assessment of reinforced recycled plastics, DFC11SI5, April 2011, Cambridge, UK

## Patent

- M Al-Maadeed, N Madi, A Hodzic, S Rajendran, 'Reinforced polymer composites from recycled plastic', US Patent US9309392B2, Status: Grant, Application Date: 18/07/2014; Grant Date: 21/01/2016