


Review

Plastic Waste Management: A Review of Existing Life Cycle Assessment Studies

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Abstract: Life Cycle Assessment (LCA) is a tool that can help to quantify the impacts of different processes to facilitate comparison and decision making. There are many potential methods for managing plastic waste, but it can be difficult to determine which methods are preferable in terms of environmental impact. Suitable existing LCA studies are identified through a screening process and the methodologies used and their outputs are compared. When undertaking an LCA, the researchers must define their scope and select their parameters, according to their aims and context, which leads to a wide variation in the approach taken. In this study, six parameters have been considered to analyze research progress in these fields regarding LCA, i.e., goals and scope, functional units, impact assessment categories, system boundaries, geographical context, and uncertainty analysis. These studies include the similar type of different studies considering plastic waste recycling, each taking a different approach to defining the system boundaries, revealing how the decision to include or exclude factors such as transport can have a significant impact on the outcomes. Additionally, compared to these similar studies on mixed-plastic waste management, different available options are used to quantitatively compare the impact outcomes, revealing how the context and parameter selection can affect the results. This review aims to highlight the prospect of LCA during the development of a waste management framework as an efficient waste recycling tool and recommend a research gap for the development of an improved management framework in the future.

Keywords: Life Cycle Assessment; LCA; plastic waste management; plastic recycling; plastic incineration



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1. Introduction

Since their invention in the 20th century, plastics have changed our lives, bringing many benefits but also huge damage to the environment. The biggest problem with plastics is that many types are incredibly long lasting and can take hundreds of years to breakdown. This is causing major problems, including the buildup of plastic pollution across the land and seas. It is estimated that 1.15 to 2.41 million tonnes of plastic are entering the ocean each year [1] and this is accumulating into huge offshore zones. The largest is known as the Great Pacific Garbage Patch which has an estimated surface area of 1.6 million square kilometers [2].

Various methods are available for handling waste plastic, from burial in landfills, to incineration, to recycling into new products. However, all of these processes have associated environmental impacts, so it can be difficult to identify the best option. One way to compare the environmental impacts of different processes is a Life Cycle Assessment (LCA), which is a method for quantifying all the different impacts a process may have on the environment, allowing comparison to other processes. A variety of research [3–7] has been conducted in this field, and a range of LCAs have been undertaken on plastic waste management. This study reviews past works, discussing and comparing the outcomes

from each. It also considers the limitations and difficulties that occur when attempting to compare results from different studies, even when they have been completed according to a standard LCA methodology.

1.1. Plastics

Plastics are a group of semi-synthetic organic compounds which are conventionally synthesized from fossil fuels, although novel bioplastics can also be synthesized from renewable biomass sources. Plastics are incredibly resistant to corrosion and are conveniently malleable, hence, can be molded into any form. With suitable additives, it is possible to vary their opacity, thickness, elasticity, and thermal properties. It is no wonder that plastic is now an integral part of human civilization.

Commonly used plastics can be broadly classified into two categories: thermoplastics and thermoset plastics. Thermoplastics soften when heated and thermoset plastics harden with heat, hence maintaining the initial form. For example, soft drink bottles and PVC pipes are thermoplastics whereas electric kettles, plugs, etc., are made of thermoset plastics. The vast majority of the world's total plastic consumption consists of thermoplastics, and these can be classified as shown in Table 1.

Table 1. Categories of thermoplastics.

Type	Abbreviation	Description	Example Use
Polyethylene Terephthalate	PET/PETE	Polyester extruded and molded. Clear, strong, and lightweight	Plastic bottles (water, soft drinks) and as packaging for many other consumer products
High-Density Polyethylene	HDPE	Intermediate level of opacity, less stretchable compared to LDPE	Milk jugs, water bottles, shampoo bottles, motor oil containers, plant pots, buckets, toys
Polyvinyl chloride	PVC	Strong, lightweight. Can be made more flexible by adding plasticizers	Plumbing pipes, doors, windows, credit cards, cable sheathing, garden hoses, toys
Low-Density Polyethylene	LDPE	High clarity and moderate stretch	Plastic bags, squeezable bottles, food containers, bubble wrap, disposable cups, coatings for paper cartons
Polypropylene	PP	Durable with a smooth finish.	Bottle tops, yogurt and margarine containers, drinking straws, hot food containers, car parts, disposable diapers
Polystyrene	PS	Economical plastics with a certain rigidity	Disposable foam cups, take-out food containers, plastic cutlery, coat hangers, foam packaging
Polycarbonate	PC	Transparent, high impact resistance	Eye protection, shatterproof glazing, UV resistant lenses, barriers, fences

Even after a century after their introduction, the yearly production and consumption of plastics continue to grow at an exponential rate, as illustrated in Figure 1. In 2015, 407 million tonnes of plastics were produced, and 322 million tonnes were consumed [8–10]. In the US, around three-quarters (27 million tons in 2018) of plastics end up in landfills [11]. When discarded to land, plastic takes roughly 500 to 1000 years to degrade, meaning that the first plastic material disposed of in landfill has not yet degraded.

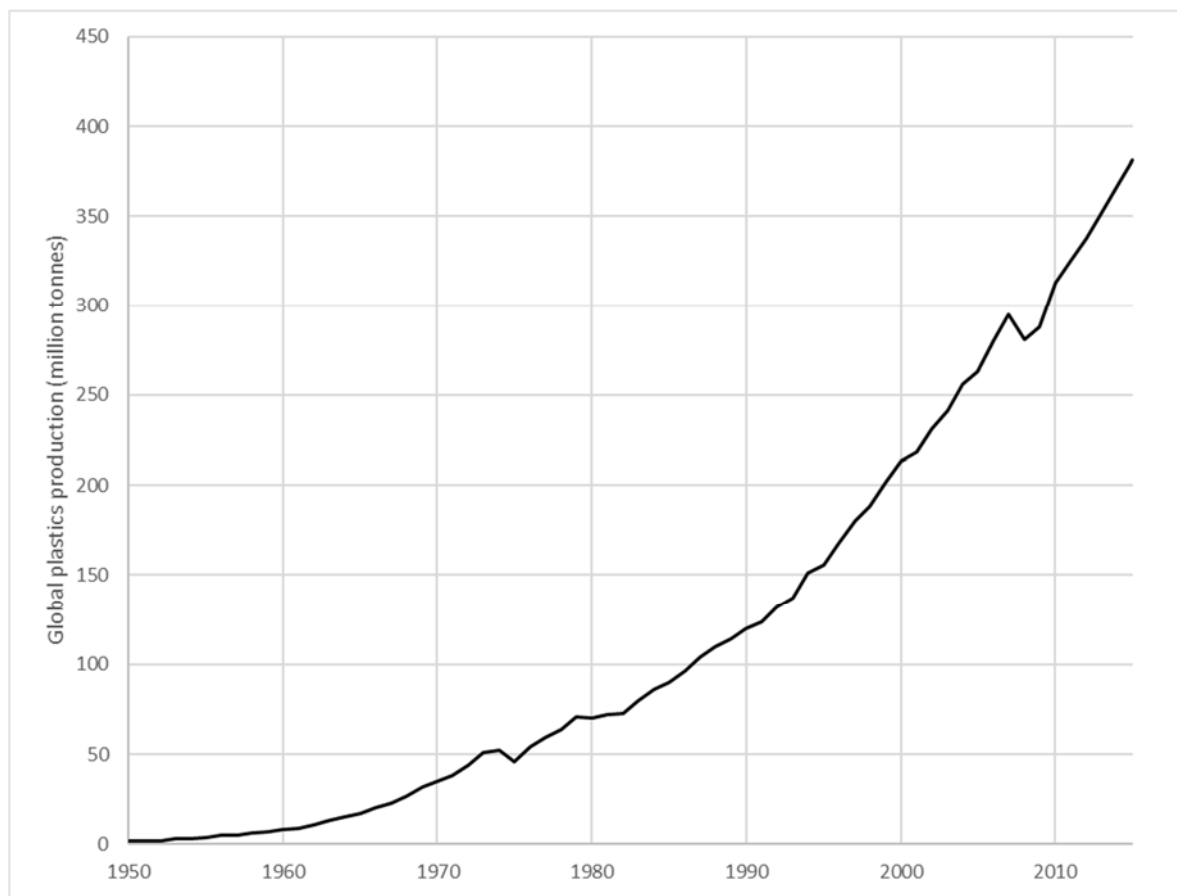


Figure 1. Global plastics production [8].

1.2. Recycling of Plastic

Plastic can either be ‘engineered’ or ‘biobased.’ Manufactured plastics are developed from unrefined petroleum, flammable gas or coal, while biobased plastics come from sustainable items such as carbs, starch, vegetable fats and oils, microorganisms and other natural substances. By far, most plastic being used today is engineered on account of the simplicity of assembling strategies associated with the handling of raw petroleum. Notwithstanding that, the developing interest for restricted oil-holds is driving a requirement for more up-to-date plastics from sustainable assets such as waste biomass or creature side effects from the business [12].

First, plastic goes through the extraction interaction. It is produced using crude materials, similar to shield the polymer from degradation by ozone or oxygen, bright stabilizers, plasticizers, oils, shades, fire retardants, enemies of statics, cellulose, furfural, oil and different petrochemicals. After plastic is created, and after it goes through its monomer preparation and assembling interaction, the subsequent stage is manufacture. During the development cycle, you end up with the finished result—tires, phones, and so on. Once the items are made, they are then bundled and dispersed to stores so we can utilize them. In the event that one throws plastic into the garbage, it will be buried in landfills. So, the cycle starts with the extraction of plastic from raw materials and production of raw plastic materials in different form is started as required. The fabrication of the output product and plastic body-based products are used. This is the end of life as far as plastic usage is concerned. The landfill process is considered to be the final stage of plastic’s life. Alternately, a mechanism could be adopted to recycle the used plastic waste, as shown in Figure 2.

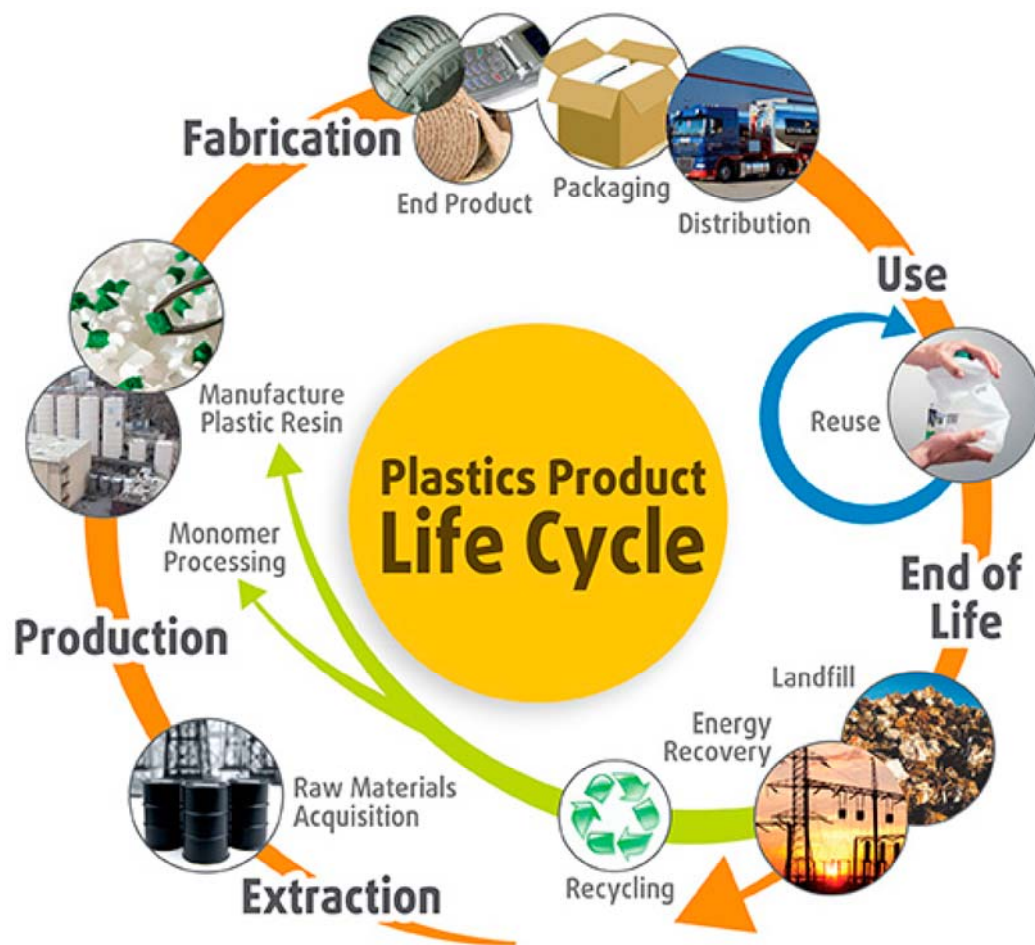


Figure 2. Plastic life cycling process [13].

The life pattern of plastic items has shown that the traditional straight model from birth to internment is an impractical interaction that brings about contamination. Plastics, for all intents and purposes, do not biodegrade, so disposed-of waste amasses on the grounds and in the oceans, getting ingested by creatures and delivering harmful synthetics to the detriment of our living surroundings. This need not be the situation. There are elective pathways plastics can take to evade their 'destiny' as waste and poisons. It is vital to investigate the prospects of the round economy and cycles such as reusing, recycling, 'refusal' and new advancements in circling the circle to give plastics new life [14].

In terms of chemistry, all plastics are basically polymers, yet not every one of the polymers are plastics. The terms 'polymer' and 'monomer' come from Greek words: where 'poly' signifies 'many,' 'mer' signifies 'rehashing unit' and the word 'mono' signifies 'one.' This, in a real sense, implies that a polymer is produced using numerous monomer-rehashing units. Polymers are bigger atoms shaped by covalently consolidating numerous monomer-units as chains, such as pearls on a pearl necklace. The word plastic comes from 'plasticus' (Latin for 'fit for trim') and 'plastikos' (Greek for 'fit for embellishment'). Plastics are additionally alluded to natural polymers (manufactured or regular) of high atomic weight, which are blended in with different substances. Plastics are high atomic weight natural polymers made out of different components such as carbon, hydrogen, oxygen, nitrogen, sulfur and chlorine. They can likewise be created from silicon iota (known as silicone) alongside carbon; a typical model is silicone bosom inserts or silicone hydrogel for optical focal points. Plastics are comprised of polymeric tar regularly blended in with different substances called added substances. 'Versatility' is the term used to portray the property, highlight and characteristic of a material that can misshape irreversibly without

breaking. Pliancy portrays whether a polymer would endure the temperature and pressing factor during the trim interaction. Science permits clients to shift various boundaries to tune the properties of polymers. Various components can be utilized for improvement, and can change the kind of monomers and modify them in various examples to change the state of polymer, its atomic weight or other compound/actual properties. This means plastics have right properties for a particular application [15].

1.3. Waste Management

Since the 1980s, the need for scientific disposal of waste plastics was recognized and, since then, there have been various attempts to identify suitable methods of plastic waste management. Currently, there are two main methods for treating plastic wastes as an alternative to landfill incineration (taking care to suppress the resulting toxic gases and chemicals) and recycling. Burning plastics is strongly advised against, as it causes the release of toxic gases into the atmosphere such as Furans, Mercury, Dioxins, and Polychlorinated Biphenyls [16]. The burning of PVC also liberates hazardous halogens and CO₂, polluting the air and causing global warming.

India is one of the largest consumers of plastic, consuming 24 million tonnes per annum [10], of which 5.6 million tonnes get discarded as plastic waste. Like many other lower-middle-income countries, India fares very poorly in plastic waste management. Lacking a centrally organized waste collection infrastructure, only 60% of plastic wastes get collected by urban municipalities (compare that to the developed countries the USA where the plastic waste collection is 98%). The rest of the plastic wastes are thrown into landfill, or worse, dumped into the ocean. In 2015 alone, India dumped 0.6 million tonnes of plastic waste into the ocean.

There has been a steady growth in the share of plastic wastes that were handled properly. In 2015, around 20% of the plastic waste got recycled and around 25% of them incinerated. Still, a larger share (55%) of the total plastic wastes went to landfill or remained unattended [9]. The processes for recycling plastic wastes can be classified into three types [17] as shown in Table 2. Primary recycling is the re-extrusion of homogeneous plastic and is not suited for post-consumer waste. Secondary recycling adds the step of mechanical processing to sort waste and reprocess into pellets which can replace virgin plastics on the market. Tertiary recycling is required for more complex mixed wastes where the plastics must be depolymerized into base molecules which can be used as a raw material for primary plastic production. All methods have their own environmental impacts which must be considered when analyzing options for plastic treatment and reuse.

Table 2. Plastic waste recycling categories.

Type	Description	Disadvantages
Primary	Re-extruding the discarded plastic wastes from industries. As a high degree of homogeneity is required by this process, post-consumer plastic wastes were not considered.	Not suitable for post-consumer plastic wastes
Secondary	Mechanical recycling of the recovered plastics. These are the plastic wastes recovered from the (retail) consumers, sorted and reprocessed to produce single polymer pellets, granules, or flakes intended to replace the virgin plastic in the market. The process primarily involves melting and extruding the plastic without altering the chemical composition of the plastics significantly.	Plastic wastes must be clean and dry, ideally consisting of only one type of plastic polymer
Tertiary	Feedstock chemical recycling, where the plastic wastes undergo pyrolysis and/or hydrolysis processes where it depolymerizes and breaks down into monomers and other basic chemical elements that can be used as raw materials for primary plastic production. This also results in the production of oil and gas which can be used as a fuel, usually used to power the recycling plant itself.	High energy consumption due to head requirements. Uses chemical reagents with negative environmental impacts

Generally, the secondary route of mechanical recycling is environmentally preferable. Depending on the number of sorting and reprocessing steps involved, it is possible to have various degrees of mechanical recycling. In a simple mechanical recycling plant, only limited polymer types are targeted (PP and PE, or PET and HDPE) and the rest of the plastic wastes are discarded. In advanced mechanical recycling plants, more polymer types are addressed. The quality and economic value of recycled plastics heavily depend on the purity of the plastic. Most industries reject recycled plastics which contain impurities (e.g., non-plastic components, non-targeted plastic, chemicals bound to the polymer matrix such as paint, etc.). Along with impurities, the form of plastic waste should also be considered. For example, if the waste contains a considerable amount of plastic films (usually used for packaging, e.g., bread bags), it can wrap around the cutting blades of the plant and clog the machinery [18].

However, feedstock recycling (Chemical and Thermal methods) has a high tolerance to plastic impurities. It can separate the non-plastic and plastic impurities from general plastic waste and recover the material (raw materials for the primary plastics) and/or the primary energy sources (fuel in the form of oil and gas). Few polymers could be recycled chemically and the processes still required significant amount of resources [19]. A cause of concern, though, is the environmental impact of a large-scale pyrolysis process. It has been shown that the stress on the environment caused by pyrolysis is similar to that of an incineration plant. Hence, it shall be utilized only as a fallback option if mechanical recycling is not suitable.

If the recycling options are not available or feasible (e.g., for poor-quality rejected plastics), then incineration can be carried out in a controlled manner to contain the toxic gases while extracting thermal energy that can be (optionally) converted into electricity. This has the environmental benefit of providing an alternative source of energy generation to fossil fuel combustion.

Therefore, every option has potentially positive and negative environmental impacts. Landfilling of the plastics at the customer location does not require any transport (saving fossil fuels) but does cause methane emission, loss of land, and pollution of land, groundwater, rivers, and seas. Incineration requires transport to plants and generates greenhouse gases, but it can be used to generate energy. Recycling reduces the production of primary plastics, but recycling plants consume energy, use/produce toxic chemicals, and requires transportation. Recycling is also not suitable in all cases, such as for plastics containing more than one type of monomer.

Assessing the advantages, disadvantages, and the technical and economic feasibility of the available options is necessary to make informed decisions on policies that could improve our quality of living and even save our planet from imminent destruction. However, there is not one clear preferential option as so many factors can influence the choice.

1.4. Legal Requirements for Waste Recycling

Waste recycling is a waste field considering different types of wastes and legal requirements according to the countries. Recycling as a source of circular economy is the major force to induce motivation in recycling. In 2020, the US Congress introduced the Plastic Waste Reduction and Recycling Act. It would

- a. Establish a waste reduction research and development program;
- b. Direct several federal agencies in developing strategies to reduce waste;
- c. Develop standards for plastic recycling technologies.

Because the US is producing 200 lbs of waste per person, a USD 85 million budget was also proposed to start this project. Different states and different countries have different bylaws to deal with the recycling of plastic depending upon their respective environmental policies. The British Plastics Federation (BPF) has developed standards on recycled content in plastic utilization. These guidelines are formatted as questions and answers. European countries, such as Germany, France, Italy, etc., are focused on developing by-laws about recyclable package development and utilization for packing.

1.5. Life Cycle Assessment

The industrial revolution resulted in an unprecedented supply of consumer products, the environmental impact of which was not adequately addressed until the 1970s [20]. By then, it was realized that the environmental damage could result from the production, transport, usage, and disposal of these goods. Thus, the concept of Life Cycle Assessment (LCA) was conceived: a tool designed to compare different processes quantitatively by measuring a range of environmental impacts. Initially, LCAs were conducted using a wide variety of different methods until the 1990s when there was a move towards the standardization and scientific foundation for LCA methodologies. Workshops and world congress held by the Society of Environmental Toxicology and Chemistry (SETAC) resulted in publications of LCA guides and handbooks such as the work by Heijungs et al. [21]. In 1994, the International Organization for Standardization (ISO) produced guidelines for conducting LCAs, which can be consulted as documents such as ISO 14040:2006 [22], and ISO 14044:2006 [23].

An LCA aims to systematically evaluate the potential environmental impacts associated with a product or service during its lifetime. The boundaries of the LCA must be defined as part of the study but may include everything from the extraction of raw materials and energy used in production, to the use and end-of-life disposal of a product. An LCA is a tool that can be used to aid in decision making. A buyer may use an LCA to compare the environmental impacts of different products or services, or a manufacturer may use it to aid with design choices.

An LCA models the process as a production system consisting of a series of interconnected unit processes whose inputs and outputs can be unambiguously defined and quantified. It is intended as a tool to conduct relative analysis, which is useful for comparing different scenarios, but it cannot predict absolute or precise environmental impacts. The ISO standards recommend that an LCA study consists of four phases:

1. Goal and scope definition;
2. Life Cycle Inventory Analysis (LCI);
3. Life Cycle Impact Assessment (LCIA);
4. Interpretation.

An LCA must be an iterative process due to the inherent complexity caused by the numerous variables involved in the study, the difficulty in collecting data, and the reliability of that data. At each stage of the study, it may be necessary to modify the goal, scope, and/or assumptions used. ISO recommends that changes occurring along the course of study should be adequately explained and reported to the target audience. It is also recommended that, for every study which intends to be disclosed to the public, a critical review must be conducted [24] to ensure the quality and reliability of the data and to verify the suitability of the approach taken.

However, researchers and organizations have the flexibility to choose the methodology which suits their goal and intended application of the study. Each Life Cycle Impact Assessment (LCIA) method aims to generate impact scores for specific categories of environmental damage (e.g., climate change, human toxicity, and resource depletion).

Different LCIA methodologies differ in their approach to achieve this goal. Midpoint methods evaluate the environmental impacts that are caused by the process being studied whereas endpoint methods focus on the result. For example, a midpoint impact might be the increased concentration of a contaminant in the air; an associated endpoint impact might be the toxicity to humans caused by this air pollution.

Endpoint methods (e.g., Eco-indicator 99 and EPS 2000) produce results that can be easier to understand because they do not require substantial knowledge of the cause-and-effect chain, but the impact scores have a high degree of uncertainty [24,25].

Midpoint methods (CML 2002, EDIP97 (and EDIP2003), TRACI, etc) can give more comprehensive results, but an understanding of the cause-and-effect chain is necessary for interpretation [24,25].

As an attempt to bridge the pros and cons of the two methods, hybrid methods (e.g., ReCiPe, IMPACT2002+) are being developed which attempt to conduct impact assessments using both midpoint and endpoint of the cause-and-effect chain. Additionally, some midpoint methods such as EDIP allow an approximation of endpoint methods by aggregating the values based on a distance-to-target method [26].

The LCA practitioner should ideally understand the strengths and weaknesses of the different methodologies and decide the appropriate one based on the goal and intended audience of the study.

1.6. Aims and Objectives

This study aims to review and evaluate the current state-of-the-art scenario based on LCA studies that have been performed relating to plastic waste management recycling, and to evaluate the benefits and limitations of making a cross-study comparison. Methodologies used and outcomes will be compared to gain a deeper awareness of the benefits and limitations of an LCA study. Where possible, LCA impact scores will be quantitatively compared and discussed in the context of gaining a greater understanding of how the methodology selection, scope, and context of the study can affect the outcomes. Limitations in comparing LCA studies will be considered by exploring how different methodologies can impact results. Finally, the study will assess the extent to which broader conclusions can be drawn from a catalog of studies.

2. Materials and Methods

2.1. Selection Criteria

Database searches (Web of Science and Scopus) were conducted searching for LCA studies that covered plastic waste management topics. A search for keywords “LIFE CYCLE ASSESSMENT”, “RECYCLING”, and “PLASTIC” on Web of Science revealed 175 records in English, and Scopus produced 275 records. The screening process illustrated in Figure 3 was followed, aiming to generate a good selection of LCA studies with a broad geographical range and using a variety of different LCIA methodologies. Review papers were excluded from the assessment criteria but were checked to identify any further references for consideration [3–7]. This produced an additional 265 references for screening.

After a check for duplicates, records were excluded which did not include a Life Cycle Assessment with methodology, did not focus on plastic waste treatment, or were not conducted within the last 10 years. Following this initial screening, the remaining 29 articles were assessed in detail, retaining those that met the following criteria:

1. An original research article focusing on environmental impacts associated with at least one plastic recycling technology.
2. Contains a well-described methodology with a clearly defined functional unit, goal and scope, and system boundary.
3. Results are quantified and tabulated as defined impact potentials covering at least two different categories.

2.2. Assessment Process

A focused comparative analysis of the shortlisted studies was conducted by working through the mandatory requirements of an LCA according to international standards [20]. The approach taken in each study was compared, specifically focusing on the sections and considerations listed below.

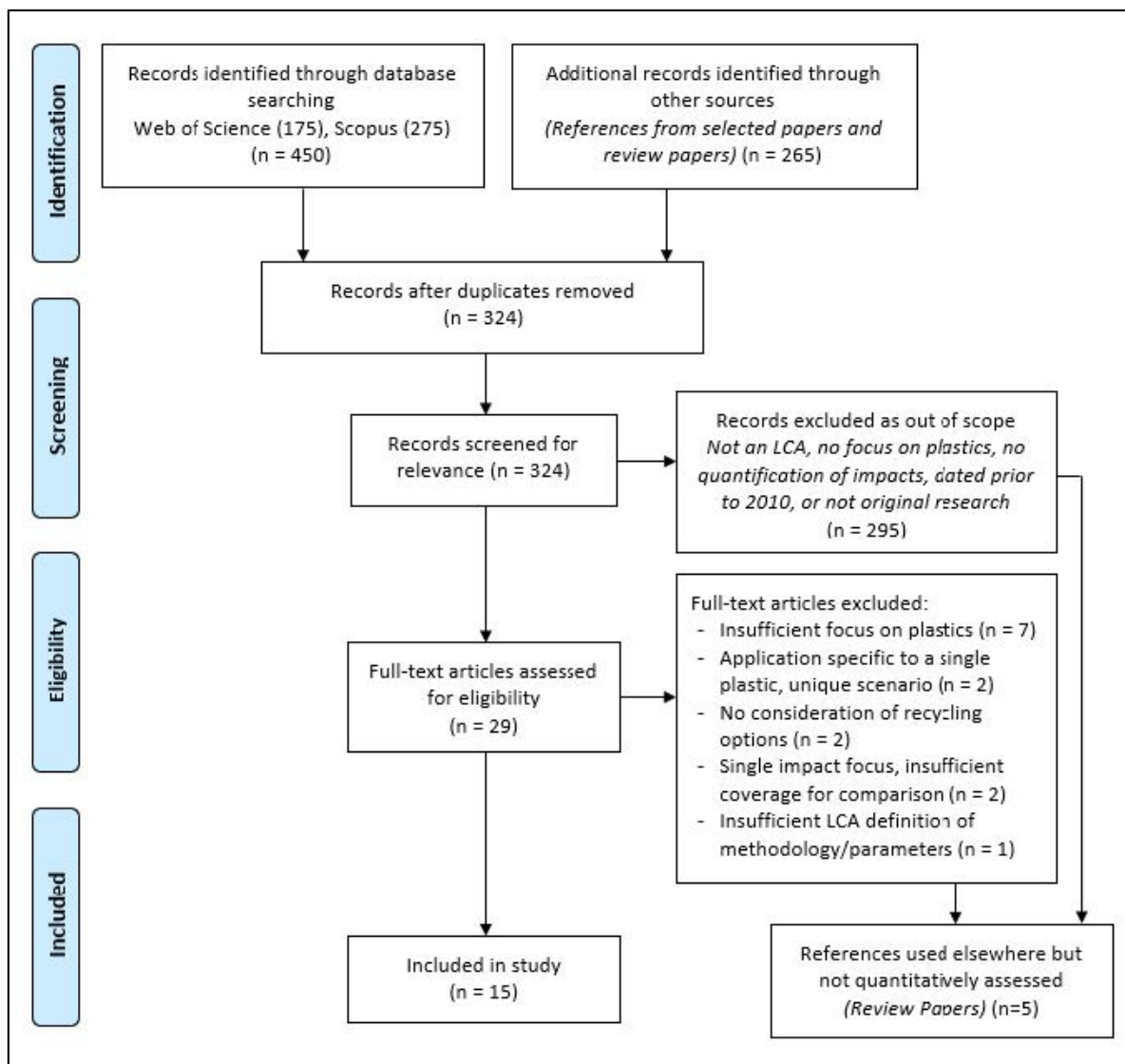


Figure 3. Research screening process.

2.2.1. Goal and Scope

The LCA phase in which the aims and breadth of the study are established.

Each study defines the goals and scope in accordance with LCA principles. This study focuses on the management of plastic wastes, so consideration is only given to impacts relating to post-consumer disposal of plastics including recycling and waste processing activities up until the point at which the material is disposed to the environment or as energy. Some LCAs may include other aspects of the plastic life cycle, from raw materials and their processing, production of consumer products, transport at all stages, sales activities, usage, right through to disposal/recovery. Researchers will also have varying overall aims and differing approaches to the selection of plastic types for study.

- Types of plastics included some studies focus on a broad range of plastics, while others were restricted to just one polymer (for example, PET) or product type (example, plastic films).
- Study extent: Some studies cover the entire lifespan of the plastics; others are more focused on specific aspects of the process.

2.2.2. Functional Unit (FU)

A quantified description of the performance requirements, enabling comparison between different systems.

For every LCA study, the resources are allocated during the Life Cycle Inventory (LCI) analysis phase, based on a defined Functional Unit (FU). The Functional Unit provides the basis for the comparison of different systems and hence is one of the most important parameters in the assessment. The researcher has the freedom to choose the FU based on their requirements, but the same functional unit must be maintained in all scenarios to ensure that environmental impact scores are comparable. In the case of an LCA for plastic recycling, the FU is likely to be based on a unit of waste.

- Type of waste (general waste, plastic waste, or specified waste type);
- Quantifier of waste amount (specific mass, volume).

2.2.3. Impact Category

Emissions are divided into categories which allows conversion of impact data into comparable units.

There is some variation in impact categories and definitions depending on the methodology used for the LCA. Common impact categories associated with plastic waste LCAs are shown in Table 3. This table shows how different emissions or environmental effects can be grouped into impact categories and given a common unit that allows different processes to be compared.

- Different studies may choose to investigate and assess different categories;
- The result for an impact category may not be comparable across studies if the system boundaries, functional units or other factors are different.

2.2.4. System Boundary

A description of the activities which are included (and excluded) from the LCA study.

Each LCA must determine the extent of the study boundaries. A broader boundary will aid a comprehensive understanding of the environmental impacts caused by the system being analyzed. However, broad boundaries will require the inclusion of a large number of unit processes, which complicated the process and increased the uncertainty associated with the analysis. Therefore, it is necessary to achieve a balance of comprehension and precision when defining the system boundary.

- Study scope (included/excluded processes);
- Geographical area (the environmental impact may vary in different locations due to varying processes, environments, infrastructures, and ecosystem sensitivities);
- Time horizon (what timeframe is considered for pollutant degradation pathways and technologies);
- Boundaries with other life cycles (how does the process interact with other processes such as plastic production, consumer use, recycling technologies).

2.2.5. Sensitivity and Uncertainty Analysis

A tool for studying the robustness of results and their sensitivity to uncertainty factors in LCA.

Sensitivity analysis seeks to determine the level of sensitivity the individual input parameters have on the LCA results (the impact category measurements). This is achieved by conducting a perturbation analysis where each of the input parameters is varied within a range of 10% of its original value while maintaining the rest of the input parameters unaffected. The set of results thus obtained are used to evaluate the sensitivity ratios and sensitivity coefficient associated with the varied parameter.

Table 3. Typical Impact Categories for Plastic Waste LCA.

Category	Description
Global Warming Potential (GWP)	<p>Increasing temperature in the lower atmosphere, caused by the emission of greenhouse gases (e.g., CO₂, methane, nitrous oxides) which reflect or absorb infrared radiations reflecting off Earth's surface. This causes regional climate changes, melting of polar glaciers, and sea-level rise. It is the most widely used impact factor for LCA studies and is also identified as Climate Change in studies using ReCiPe (Endpoint) or Ecoindica-tor99.</p> <p>Expressed as kilograms of CO₂ equivalent.</p>
Ecotoxicity Potential (ETP)	<p>Ecosystem impact of the emission of toxic substances to air, water, and soil can have a global, continental, or local scale. The plastic industry contributes to the toxicity caused by emissions of toxic substances (e.g., diethyl phthalate). Some LCIA methods, such as ReCiPe, combine the toxicity affecting air, water, and soil to one parameter, others, such as CML, divide these into terrestrial, freshwater, or marine ecotoxicity potentials.</p> <p>Normalized and expressed as 1,4-dichlorobenzene (DB) equivalents/kg emission.</p>
Acidification Potential (AP)	<p>Impact of processes that cause acid rain and reduced vegetation, usually caused by the emission of chemicals (e.g., sulfur oxides, nitrogen oxides, and ammonia). Acidification can reduce the pH of soils, freshwater resources, and seas.</p> <p>Terrestrial Acidification Potential (TAP) is a subcategory related to acidification of soil, caused by landfilling of plastic and/or other chemicals. Expressed as kilograms of SO₂ equivalents.</p>
Abiotic Depletion (elements) (AD)	<p>Use of natural resources, including minerals and energy, but excluding fossil fuels. The natural resources can be renewable (quickly replenished) or nonrenewable (not replenished within 500 years).</p> <p>Expressed as kilograms of Antimony equivalent (kg Sb-eq).</p>
Abiotic Depletion (Fossil Fuels) (FDP)	<p>The use of fossil fuels (non-renewable), this category is also known as Fossil Depletion Potential.</p> <p>Expressed in MJ of energy produced.</p>
Eutrophication Potential (EP)	<p>The enrichment of aquatic ecosystems with nutritional elements (e.g., nitrogen and phosphorus compounds). Causes excessive algae growth, which releases toxins harmful to higher energy forms, and reduces light and oxygen in the water, harming other aquatic life.</p> <p>Expressed as kilograms of PO₃– equivalents.</p>
Human Toxicity (HT)	<p>The effect of toxic substances on human health is sometimes expressed in subcategories of HT (cancer) and HT (non-cancer) depending on whether the substance is carcinogenic.</p> <p>Expressed as 1,4-DB equivalents/kg emission of substance.</p>
Photochemical Oxidation Potential (POP)	<p>Formation of ozone at the troposphere (ground level), also known as Photochemical Oxidant Formation, (Photochemical) Ozone Creation, or Ozone Formation. The photochemical oxidants are secondary air pollutants (also called summer smog) formed by the reaction of sunlight on carbon monoxide, and reactive hydrocarbons (e.g., ethane) in the presence of nitrogen oxides.</p> <p>Expressed as kilograms of ethane equivalent.</p>
(Stratospheric) Ozone Depletion POTENTIAL (ODP)	<p>Emissions of stable substances containing Chlorine or Bromine to air can reach the stratosphere and destroy the ozone layer. Depletion of the ozone layer increased the UV rays reaching the earth's surface, which is harmful to humans, plants, and animals.</p> <p>Expressed as kilograms of CFC-11 equivalents.</p>
Particulate Matter Formation Potential (PMFP)	<p>Measure of particulate matter (PM10) release to the air. This consists of respirable particles with a diameter < 10 µm, that are hazardous to human health. Primary particles (e.g., nitrogen oxides, sulfur oxides, ammonia) react to form larger diameter secondary substances (e.g., ammonium nitrate, ammonium sulfate).</p> <p>Expressed as kilograms of PM10 equivalent.</p>

3. Results

A total of 15 suitable LCA studies were identified and selected for this review. These are shown in Table 4.

Table 4. Selected studies and their parameters.

Publication	Plastic Type	Functional Unit	LCIA Technique	Impact Categories
2010 T. Chilton et al. [27]	PET soft drink bottles.	1 tonne	Eco-indicator	GWP, ETP, AP, FDP, EP, Carcinogens, Respiratory organics, Respiratory inorganics, Radiation,
2012 C.-E. Komly et al. [28]	PET bottles	M kg	CML 2001	GWP, ETP (freshwater and terrestrial), AP, AD, EP, HT, POP
2012 M. Al-Maaded et al. [29] 2012 Nishijima et al. [30]	Mixed plastic waste Waste plastic container	10 kg 1 kg	CML 2001	GWP, AD, HT GWP, FDP
2013 S Rajendran et al. [31]	Polyolefin plastic wastes	1 tonne	Eco-indicator, EDIP	GWP, ETP, AP, AD, EP, HT, POP, ODP, hazardous and radioactive waste, slags/ashes, bulk waste
2014 S.M. Al-Salem et al. [32]	Plastics mix (VCC feed), PO (PP + PE), PVC Packaging waste	1000 tonnes per annum	CML 2001	GWP, ETP, AP, POP
2014 S. Ferreira et al. [33]	including (PS, PE, PET, mixed plastics)	32,645 tonnes	CML 2001, ReCiPe	GWP, ETP, AD, EP, HT, POP, renewable and non-renewable energy
2014 L. Rigamonti et al. [34]	PET, HDPE, LDPE	1000 tonnes per annum	CML 2001	GWP, ETP, AP, POP
2015 P.A. Wäger, R. Hischer [35]	Mixed, plastic-rich residues from WEEE treatment	1 tonne	ReCiPe	GWP, ETP (marine, freshwater and terrestrial), AP, FDP, EP, HT, POP, ODP
2017 F. Gu et al. [36]	Recycled plastic mainly PP and PE	1 tonne	ReCiPe	GWP, ETP (marine, freshwater and terrestrial), AD, AP, FDP, EP, HT, POP, ODP, PMFP, ecosystem diversity (ED)
2018 P. Hou et al. [18]	Plastic film waste, mixed waste	1 tonne	TRACI	GWP, AP, AD, FDP, EP, HT, ODP, habitat alteration, water intake, Indoor air quality
2019 Y. Aryan et al. [10]	PET, PE	1 tonne	CML 2001	GWP, ETP (marine, freshwater and terrestrial), AP, AD, FDP, EP, HT, POP, ODP
2019 G. Faraca et al. [17]	Post-consumer hard plastic (films and PVC)	1 tonne	Undefined	GWP, ETP (terrestrial), AP, HT (cancer, non-cancer), POP, ODP, PMFP
2019 H.H. Khoo [37]	Plastic waste	822,200 tonnes	ReCiPe	GWP, AP, PMFP
2019 Y. Chen et al. [38]	PP, PE, PVC, acrylonitrile-butadiene-styrene (ABS), PS, PET	1 tonne	ReCiPe	GWP, ETP (marine, freshwater and terrestrial), AP, FDP, EP, HT, POP, ORP, PMFP, WDP (water depletion potential)

3.1. Comparison of LCA Goals and Scopes

The majority of studies about the LCA of plastic wastes compare the environmental impacts associated with different disposal options. However, the aims of each study vary and this is reflected in their scope and selection of parameters for the LCA. Key differences related to the type of plastics studied and the extent of the life cycle analyzed (whether an 'end-to-end' approach is taken or the focus is on a specific process).

Two of the studies compare processes for the disposal of PET soft drinks bottles but they have different goals and scopes. Chilton et al. [27] compared the impacts caused by the incineration process versus the recycling process of PET bottles in the UK. The study looks at the post-consumer collection of the discarded PET bottles and follows the impacts caused by the process leading to its final end-of-life destination as products of incineration or its incorporation into new bottles through recycling (landfill of materials rejected by both processes is kept outside the scope of the LCA). In a similar study by Komly et al. (2012) [28], the entire life cycle (cradle to grave) of PET bottles in France was analyzed, comparing mechanical recycling, feedstock recycling, and incineration.

Many of the recent studies [10,16,32,37,38] focus on the treatment of mixed plastic wastes, but again there is a wide variation in goal and scope. All have a general goal of comparing the impacts of different treatment options for mixed waste plastic although Faraca et al. [16] also included an economic analysis. All studies focused on waste manage-

ment processes specific to their location and this highlights some of the major differences in practices around the world. Many of the studies involved waste that was collected pre-sorted, while Al-Maaded et al. [29] considered mixed municipal waste in Qatar, which included non-plastics. Aryan et al. [10] found that although India lacks waste management infrastructure, it ranks second for the recycling of PET bottles (around 90%), thanks to the rag collectors and MRF centers, and small PE recycling industries. The studies generally share a common goal of comparing mixed-plastic waste disposal methods such as mechanical recycling, waste-to-energy, and landfill. For this reason, these studies were largely comparable, except Al-Maaded et al. [29] whose inclusion of non-plastic wastes meant that the scope differed significantly from the others.

Several studies focus on the management of packaging wastes (mostly plastic films) [17,30,33] but these differ quite considerably in their goals and scope. Nishijima et al. [30] conducted an extensive analysis of 27 scenarios that can be potentially used for packaging waste processing in Japan. The analysis included various combinations of mechanical recycling followed by disposal, feedback recycling and disposal, and plastic tray recycling aided by individual corporates. Mixing waste plastics with other combustible wastes and incineration with energy recovery is also considered. Ferreira et al. [33] studied the environmental benefits of a 2010 Portuguese waste management initiative where packaging wastes (including PS, PE, PET, mixed plastics, glass, paper/cardboard, Aluminium, and steel) were collected by the authorities for recycling. The study compared this process, including the incineration or landfill of residues from the recycling plants to the previous baseline options of only incineration and landfill. Later, Hou et al. [18] studied the environmental impacts of end-of-life treatment of plastic films including the packaging in the USA. They used data available from various references to assess waste collection and waste composition scenarios including landfill disposal, incineration, and recycling of plastic films in recyclable and mixed wastes.

The other LCA studies considered in this review focus on specific applications or scenarios related to plastic waste management and have widely differing goals and scopes. Wager et al. [35] conducted a study on how waste electrical and electronics equipment (WEEE) is processed in Europe. The plastic-rich mixed residues from the mechanical treatment of WEEE are recycled and the post-consumer recycled (PCR) plastics are reintroduced in the market as a replacement for primary plastics. The fraction of PCR that gets rejected in the market goes to an incineration process and converted to energy. The goal of the study is to assess the environmental impacts compared to direct incineration without recycling. The study also considers the impacts of using PCR plastic granules compared to primary virgin plastics for the manufacture of products. The processing of polyolefin plastic wastes in the UK was analyzed by Rajendran et al. [31], comparing mechanical recycling with energy recovery through incineration. In this study, the authors also compared three different LCA methodologies for assessing the environmental impact (EDIP 2003, CML 2001, and Eco-indicator 99). Rigamonti et al. [34] studied the advantages of source separation of plastics. In the baseline scenario, mixed plastics (PET, LDPE, HDPE, and plastic films) are collected and incinerated (90%) or sent to a mechanical-biological treatment plant (10%). The alternate scenarios considered were source separation a recycling or PET and HDPE bottles only; source separation and recycling for all plastics (with the residue used as fuel in cement kilns as a replacement for coal); plastic and metal 'dry-bin' collection followed by mechanical sorting; and no source separation for plastic, but mechanical sorting using near-infrared scanners (NIR). Gu et al. [36] studied the operation of Shanghai Tianquang Industrial Co. Ltd. in Shanghai, a company that produces plastics from both virgin and recycled materials. They collect rejected products, plastic components from dismantled WEEE, plastic waste from Shanghai, and imported plastic wastes from abroad. The study aims to compare the environmental impacts of the different recycling routes and to evaluate how recycled plastics compare to virgin plastics.

3.2. Comparison of Functional Units

As shown in Table 4, most studies selected a functional unit (FU) based on a unit of mass of plastic.

Chilton et al. [27] opted for a FU of 1 tonne of PET bottles, while a similar study by Komly et al. [28] featured a functional unit of M kg of virgin PET bottles. This was the only study in this review where the functional unit was kept as a variable.

For mixed plastic studies, an FU of 1 tonne was a common choice [10,17,38], although Al-Salem et al. [32] opted for 1000 tonnes and Al-Madeed et al. [29] used a value of 10 kg. Khoo et al. [37] decided to use a 'generation-based' FU of 822,200 tonnes, representing the amount of plastic waste generated in Singapore per annum.

Many of the specialist studies also used a FU of 1 tonne, relating to the specific waste type being studied [17,31,35]. Ferreira et al. [33] defined a FU of 32,645 tonnes which equates to the quantity managed by the Portugal composting facility in 2010. Gu et al. [36], took a slightly different approach, based on the output rather than the input, with an FU of 1 tonne of product from the recycling routes defined in the system. Finally, Nishijima et al. [30] defined a FU as 1 kg of packaging wastes containing 0.151 kg of impurities.

3.3. Comparison of Impact Assessment Categories

Table 4 also summarizes the impact categories that are considered in each study. This is generally dictated by the choice of LCIA technique that is followed.

3.4. Comparison of System Boundaries

In many of the studies, the system boundary starts from the post-consumer collection of the waste materials and ends when the plastics have all been accounted for through recycling, or incineration, landfill [10,18,27,30,31,34,36]. Some studies exclude the waste collection element from the study [17,32,33,38], instead, the system boundary starts from the point of waste sorting, again ending with recycled products, energy generation, or landfill disposal.

In other studies, a different approach is taken. Khoo et al. [37] do not explicitly state the system boundaries, but it can be inferred that they have included processes from the post-consumer collection of plastic wastes, waste to energy processes, and transportation (by barge) to landfill.

Komly et al. [28], take an all-encompassing 'cradle-to-grave' approach, including the production of PET bottles starting from the raw fossil materials, right through to their ultimate destination, even accounting for the possibility of multiple recycling trips.

Wäger et al. [35] take a two-stage approach; in the first case, the system boundary starts with materials obtained from a WEEE processing facility and includes analysis of incineration and recycling processes. In the second stage, the system boundaries are modified to aid comparison against virgin plastics, starting from WEEE treatment through to production of the recycled products, energy, and landfill of residuals.

System boundaries defined in the various studies are summarized in Table 5.

Table 5. System Boundaries.

Publication	Start-Process	Intermediate Processes	End Products/Process
2010 T. Chilton et al. [27]	Post-consumer collection	PET recycling, transport of the PET granules, chemical/physical treatment, transport to the bottle manufacturing plant	Manufacture recycled bottles Landfill of discarded products
2012 C.-E. Komly et al. [28]	Raw fossil material	Production of PET bottles, recycling, incineration, landfill, possibility of multiple recycling trips included	Recycled product, landfill or incineration
2012 M. Al-Maaded et al. [29]	n/a	n/a	n/a ¹
2012 Nishijima et al. [30]	Post-consumer collection (curbside collection and at retail points)	Mechanical and feedstock recycling and incineration, energy recovery. Recovered materials and energy generated are subtracted from the system	Recycled product, landfill or incineration
2013 S Rajendran et al. [31]	Post-consumer collection	Recycling and WTE processes, including the transport of the residues, were included within the boundary	Recycled product, landfill or incineration
2014 S.M. Al-Salem et al. [32]	Sorting	MRF and two thermochemical treatments, VCC, and LTP.	Recycled product, landfill or incineration
2014 S. Ferreira et al. [33]	Sorting	Waste management processes by a Portuguese local authority including recycling of plastics. Comparison to landfill and recycling scenarios	Recycled product, landfill or incineration
2014 L. Rigamonti et al. [34]	Post-consumer collection	Recycling processes, waste-to-energy, and mechanical/biological treatments of the residuals	Recycled product, landfill or incineration
2015 P.A. Wäger, R. Hischer [35]	Stage 1: WEEE treatment output Stage 2: WEEE treatment	Stage 1: transportation and recycling or incineration of plastic-rich materials resulting from WEEE processing Stage 2: transport of the plastic-rich residues to recycling facility, production of PCR plastics. Comparison to virgin plastic production	End products: heat and power, fuel for clinker production; plastic (mix); metals
2017 F. Gu et al. [36]	Post-consumer collection	Defined by company processes for sorting, recycling, and production of materials and energy.	Recycled product, landfill or incineration
2018 P. Hou et al. [18]	Post-consumer collection (curbside and consumer drop-off)	Various end-of-life routes of plastic films included. Energy and recycled plastics generated are allocated as negative outputs of the system, indicating the reduction of resource use.	Recycled product, landfill or incineration
2019 Y. Aryan et al. [10]	Post-consumer collection	Waste treatment processes—landfilling, incineration, and recycling of PE and PET. Comparison to virgin PE/PET production	Recycled product, landfill or incineration
2019 G. Faraca et al. [17]	Sorting	All MSF processes but excludes waste collection	Recycled product, landfill or incineration
2019 H.H. Khoo [37]	Post-consumer collection	System boundaries are not explicitly stated in their report, but it can be inferred that all processes from collection to energy generation and landfill are included.	Transportation to mainland landfill by barge from Singapore City
2019 Y. Chen et al. [38]	Sorting	Cleaning and sorting, transport to landfill, incinerator, or recycling facility, and processing accordingly. Collection of wastes is excluded	Recycled product, landfill, or incineration

¹ System boundaries not comparable as the study does place sufficient focus on plastic wastes.

3.5. Comparison of Geographical Context

The geographical setting can also have a significant impact on the findings of a study. There is a wide variation in the social and economic development indices among the various countries included. Depending on the status of each country, the priorities of the society differ. This is a time when the whole world is starting to realize the looming threat to the future of the planet in the form of global warming. While all countries seem to understand it as a real threat, only a handful of countries have started to take real actions to counter that. The awareness of climatic changes and the ability/resource to take action is generally greater in the developed countries. This fact is evident from the number of LCA studies arising from these countries. The majority of Life Cycle Assessment studies are conducted in Europe, as reflected in this review; 8 out of 15 of the shortlisted studies originated from European countries [17,27,28,31–35]. Six were from Asia (China [36,38], Japan [30], Singapore [37], Qatar [29], and India [10]) and one originated from the USA [18].

LCA studies require a large amount of operational data, with high accuracy to come up with useable results. The unavailability or unreliability of available data is the major reason behind the scarcity of LCA studies in developing and under-developed nations. The work of Aryan et al., the only paper of Indian origin shortlisted in this review, can be taken as an example. As per the study [10], the collection of plastics from households of the city of Dhanbad was conducted by rag-pickers, using hand-pulled carts or sacks to carry the plastic wastes to the nearest retail waste collection centers. There are no accurate data available on the number of rag pickers or quantities of plastic wastes collected at any centralized source. This means that extensive surveying is required to collect data needed for an LCA study. Other studies do not have these difficulties; for example, Gu et al. [36], were able to make use of operational data held in company databases.

There is also location-dependent variability in the relevance of the scenarios considered as well. For example, the different ways of waste separation analyzed by Rigamonti [34] have high relevance in Europe and other developed countries but have little relevance in India and other countries where rigorous segregation of waste is not practiced. It is also possible that many recycling, feedstock, waste-to-energy options for plastic waste management practiced in developed countries are not feasible in developing countries, where landfilling and incineration without energy recovery are still the primary ways to dispose of plastic wastes. Therefore, the goals and focus of LCA studies may differ depending on the location and setting. In some cases, an LCA may aim to provide data that will steer decision making by governments or businesses, in other cases the intention may be to raise public awareness on the dangers of mismanagement of plastic waste and encourage people to change habits.

3.6. Sensitivity and Uncertainty Analysis

Some of the studies included a sensitivity analysis which helps to gain an understanding of the uncertainty levels in the final impact assessment evaluations.

Komly et al. [28] evaluated uncertainties related to each of the impact parameters by applying a Monte Carlo analysis on the probability distributions used to approximate input data variations for eight valorization routes. The resulting uncertainties varied widely for each parameter. The highest variation was seen in the freshwater and marine ecotoxicity impacts which had coefficients of variation (CV) exceeding 80%. The least affected impact parameters were GWP (CV < 10%), ADP (<13%), AP (~14%), EP (~14%), and POP (~14%). The variations on other parameter values ranged between 30 and 60%. The sensitivity analysis demonstrated that GWP and ADP are sensitive to sorting efficiency and mechanical recycling efficiency at the MRF. Transportation distance for waste collection had a negligible sensitivity on the final values of the impact parameters.

The sensitivity analysis conducted by Wager [35] showed that the composition of the WEEE has a negligible influence on the overall impacts. Hou et al. [17] used sensitivity analysis to show that the impact values are least sensitive to the collection distance and electricity/diesel consumption at the MRF. The parameters which have the maximum

influence are the utilization of the combustion energy recovered, the utilization of the recycled plastic, and the recycling efficiency of the MRF. Additionally, the mass fraction of plastic film present in the waste is a significant parameter that influences LCIA values for most categories.

4. Discussion

This review demonstrates some of the difficulties in making comparisons between LCA studies. Even when studies share identical objectives, there are a huge number of variables that will influence the output. Researchers may follow different LCA methodologies, they may select different functional units and different system boundaries. To analyze the data, a researcher has to make various assumptions and decisions about the inputs and outputs of the system, its unit processes, the level of details to include, the allocation process during inventory analysis, and various other factors. The geographical setting also plays a role, as waste management processes vary significantly between different nations and in different contexts. The context of each study also influences its aims, methods, data availability, and scope.

However, it is still possible to qualitatively compare, the relative environmental impacts of various alternatives based on the impact categories under consideration. Such comparison helps reveal uncertainties or loopholes in any of the studies. Where studies have been conducted at different periods or in different geographical locations, the results might provide valuable insight into the temporal, cultural, or geographic influences involves.

4.1. Comparable Studies

In the context of this review, there are several papers with sufficient similarity to allow for partial qualitative comparison. Consider LCA studies by Chilton et al. [27] and Komly et al. [28], both of which analyzed end-of-life options for PET bottles. A major difference between the two studies was the system boundary definition. Chilton analyzed impacts from a post-consumer starting point, following a zero-burden assumption, whereas Komly took a 'cradle-to-grave' approach, following the entire life cycle of the PET bottles starting from their primary production. Both studies compared the impacts of incineration (with energy generation) to multiple recycling options, but they used different LCIA methodologies (Eco-indicator and CML, respectively). Although the impact categories differed depending on the LCIA methodology used, three common categories were identified: Global Warming Potential (GWP), Acidification Potential (AP), and Abiotic Depletion Potential (ADP). Chilton found that the recycling option was environmentally advantageous in all categories. For both AP and ADP, the WTE option gave a negative score, indicating the environmental benefits associated with reducing fossil fuel requirements avoiding acidification caused by the landfill. However, these values were dwarfed by the alternative recycling option which was calculated to be 6.5 and 5.5 times more environmentally friendly for AP and ADP, respectively. For GWP, as expected, the WTE gave a positive impact value due to the greenhouse gas emission from incineration (around 60%) compared to that corresponding to the recycling option, which was normalized at 100%, indicating the reduction in the production of primary plastics. This may also be influenced by the choice of system boundary since the recycled bottles were assumed to replace fresh PET bottles and the impacts of incineration or landfill at their end-of-life were not considered. Komly [28], on the other hand, exhaustively followed the life cycle of every PET bottle and thus obtained different results from Chilton. For the WTE option, all three category indicators: GWP, AP, and ADP were positive (95%, 75%, and 70%, respectively). For the recycling option, the relative impact values obtained were +5%, 25%, and 30%, respectively. The positive value of the GWP was due to the greenhouse gas emission caused by the additional transport required by the recycled PET bottles. This comparison illustrates the influence of system boundaries on the results obtained.

Four LCA studies compare three similar alternatives for mixed-plastic waste treatment, albeit in different countries around the world. All four studies compared impacts from

mechanical recycling facility (MRF), waste-to-energy (WTE) residue waste incineration, and landfilling of the residue wastes. However, the researchers used different methodologies for evaluating the impact assessments (CML and ReCiPe) meaning that only two comparable impact categories were included (acidification potential, AP and global warming potential, GWP). Table 6 shows how the results compare (note that the normalization method used in each of the studies differs).

Table 6. Comparison of Impact Assessments Results for four mixed-waste treatment LCAs.

Impact Category	Reference	Location	MRF	WTE	Landfill
GWP	Al-Salem et al. (2014)	UK	−12	72	16
	Aryan et al. (2019)	India	11	51	38
	Chen et al. (2019)	China	−165	59	6
	Ferreira et al. (2014)	Portugal	−1	99	0
AP	Al-Salem et al. (2014)	UK	−43	−52	2
	Aryan et al. (2019)	India	17	22	61
	Chen et al. (2019)	China	−83	−20	3
	Ferreira et al. (2014)	Portugal	−56	−29	15

As Table 6 shows, mechanical recycling (MRF) generally has better performance in terms of reducing global warming and acidification of the environment. Except for Aryan's study, the MRF alternative consistently yields a negative impact value for both GWP and AP, which corresponds to a positive effect on the environment. However, the extent of compensation varied from study to study, depending on local parameters and the assumptions made. For example, Chen et al. report a very high GWP impact value of −165% for the MRF, but this is based on an unrealistic assumption that the substitution rates for the recycled plastics were 100%, meaning all the recycled plastics were used up in the market. Other studies took a more conservative approach: Al-Salem assumed a substitution factor of 0.5, while Aryan opted for 0.8 (based on 90% of plastic wastes recycled, and 92% of weight retained after the recycling process). Ferreira et al. assumed that all the replaced plastics were used in the furniture industry and based the calculations on the replacement of plywoods rather than plastics, resulting in a smaller GWP impact value of −1%.

Similar discretion is needed while comparing the results obtained for the WTE option by the four studies. It is known that the incineration process emits greenhouse gases, but it also generates thermal energy and electricity which can be used as an alternative to fossil fuel consumption. However, the results indicate that overall, the WTE option contributes adversely towards the global warming problem, with all high positive impact values between 50% and 100%. However, all four studies indicated a negative impact value for AP, indicating that the incineration process is advantageous in reducing the impact of acidification, making it the second most environmentally friendly method of disposal, and suitable for disposal of the residues discarded by the MRF.

Landfilling is by far the least preferred option among the three overall, but the landfill operation itself does not directly contribute towards GWP. The GWP impact value associated with the landfill option relates to the transportation of wastes to the dumping sites. In all other impact factors, including EP, HT, ADP, ETP, landfilled plastic is a major adverse contributor to environmental damage, as illustrated by the AP values in Table 6.

4.2. Other Studies

The other studies differed considerably in their scope and approach or scope, which prevents useful comparison on the detail. However, they all provided an overall conclusion relating to the environmentally preferable treatment methodology, which can be compared as follows.

Rajendran's analysis [31] indicated that the mechanical recycling of the plastic is preferred over the incineration option only if at least 75% to 80% of the virgin plastics can

be replaced by recycled plastics. If the substitution ratio is lower, the amount of residue requiring disposal causes a net adverse environmental impact. A similar conclusion was reached by Faraca et al. [17] who showed the benefits of using an advanced mechanical recycling facility to reduce the amount of residue, increasing secondary plastic production, and associated revenue.

Nishijima [30] considered 27 potential combinations of four basic disposal methods and concluded that the preferred option is mechanical recycling, followed by independent trey recycling from the residues, the residues of which are taken up by the coke-oven feedstock recycling. If restricted to two methods, mechanical recycling followed by feedstock recycling is preferred. Similar conclusions were reached by Rigamonti [34] who found that no single disposal method came out as the best overall impact categories, but substantial improvement is possible if multiple processes are aptly queued (e.g., mechanical recycling followed by the WTE of the residue). Rigamonti also found that mechanical sorting of different plastic types using near-infrared sensors is preferable to source separation.

For WEEE processing, Wager [35] estimated that the recycling of plastics from WEEE is 4 times better than the incineration option and also 6 to 10 times better than primary plastic production. Hou et al. [18] discovered that it is currently more efficient to recycle plastics from mixed wastes than from recyclable wastes. This is because the consumers regularly dispose of the recyclable plastic films in the mixed waste bin, leading to a larger weight fraction of the recyclable plastic in the mixed waste. This means efficiency and hence the environmental benefits could be significantly improved with better source segregation. This study also found that consumer drop-off points were not environmentally favorable compared to other options due to fuel usage. Finally, Gu et al. [36] concluded that the centralized recycling of plastic waste yields the most benefits compared to the non-centralized routes.

4.3. Summary

As this review illustrates, it is very difficult to compare different LCA studies. Most studies are designed to meet a specific need or goal which may be very localized to the region, company, or site. Even when project goals and scopes align, the LCA practitioners may choose to follow different methodologies which may focus on different impact categories and produce different results. System boundaries can differ according to local factors outside of the studies process—for example, waste composition, collection, and sorting practices vary around the world. Treatment options also vary depending on the technologies and resources available with consideration to the market value of any outputs (recycled products, energy). Local government can also influence waste management outcomes through policies or incentives.

Any attempt to quantitatively compare impact potentials between different studies should be approached with caution, with consideration to the differences between the study methodologies. However, although the detail might differ, there is value to be gained from comparing the general conclusions across different LCA studies with similar goals. Overall, this review found that for all the studies which aiming to compare waste treatment technologies, mechanical recycling comes out as the environmentally preferable option in most cases, although many studies reported that this was only true in certain scenarios.

However, a comparison of LCAs is useful in highlighting studies that yield differing results, as the reasons for the difference can be explored giving greater insight into some of the critical factors involved. For example, by investigating why Komly et al. [28] did not find mechanical recycling of PET bottles to be as favorable as Chilton et al. [27] reported, this illustrates that the main difference is due to the inclusion (in Komly's case) of the impacts associated with transport.

5. Conclusions

Life Cycle Assessment is a good way to quantify a wide range of environmental impacts, especially when comparing different scenarios. However, the variety of LCA

techniques and the need for researchers to establish project-specific parameters, means that the results from one LCA are rarely comparable to another. Research aims, approach, geographical location, local context, system boundaries, and other parameters all have a significant impact on the study and its outcomes.

Nevertheless, the exercise of comparing studies and considering why differences occur is very valuable in providing a deeper understanding of the parameters which influence environmental impact. This can generate new knowledge, for example, revealing how certain small changes can have a big effect on the overall impact of a process, or how processes can be combined most efficiently to reduce adverse outcomes. Sometimes LCA studies demonstrate a counter-intuitive result, perhaps revealing that a process widely believed to be environmentally beneficial may have hidden impacts, the extent of which had not previously been quantified.

When attempting to compare different LCA studies, it is recommended that a thorough comparison of the LCA methodologies used, the system goals and boundaries, and the local factors influencing the process itself. Importantly, it is necessary to understand where these align and where they differ and the effect this has on the results. While deciding about the management of plastic waste and recycling it, LCA perspective should be considered for efficient and durable utilization of resources. So, in a waste management framework, LCA is a necessary parameter to be studied for long-term benefits.

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