Macromolecular Chemistry and Physics
www.mcp-journal.de

Design for Recycling Strategies Based on the Life Cycle Assessment and End of Life Options of Plastics in a Circular Economy

Venkateshwaran Venkatachalam, Merlin Pohler, Sebastian Spierling, Louisa Nickel, Leonie Barner, and Hans-Josef Endres*

The plastic economy, despite offering unique properties in fulfilling the functions of products in different industrial sectors over decades, has so far been mainly linear, that is, "take-make and dispose" with only a small fraction of plastics being recycled worldwide. With ever-increasing circular economy initiatives and the urge to conserve resources and prevent plastic pollution from affecting ecosystems, more emphasis on the resource recovery of plastic products after its use has been made over the last few years. It is necessary for manufacturers to understand the value chain as early as the design phase while manufacturing and distributing plastic products across the world. The current study provides an overview of the status quo of plastic waste management and analyzes the Life Cycle Assessment (LCA) studies of different End-of-Life (EoL) options for plastics. Based on the LCA studies, a preliminary, country-specific Circular Footprint (CF) is calculated and Design for Recycling (DfR) strategies are identified. Results show that the environmental impacts of different EoL options differ significantly for different plastics. The CF highlights the lack of data regarding the composition and recovery of plastics in different countries thus showing the necessity to consider the whole lifecycle when quantifying the environmental impacts of plastics.

1. Introduction

Plastics have been evolving during the last century into a versatile material group that is used for products ranging from packaging to building materials. In the timeframe from 1950 to 2015, approximately 8300 Mio t. plastic were produced. While only 600 Mio t. was recycled, the main share of 5700 Mio t. was disposed of or incinerated.[1] This highlights the current linear economy character of the plastic economy. Due to the low cost of polymers as well as versatile types of products manufactured from plastics (using a broad range of additives), recycling infrastructure and circular economy for plastics is still in its early developmental phase.

Against the backdrop of limited resources, a growing global population and other sustainable challenges like climate change, marine litter (LI), and associated challenges with toxicity in ecosystems[2] it is imminent to improve the circularity of plastics and its products. Tackling plastic pollution and sustainable consumption of plastics have also become an integral part of the Sustainable Development Goals (SDGs) globally. The United Nations Environmental Assembly has even adopted a declaration, to significantly reduce the manufacturing and use of single-use plastic products by 2030.[3]

To increase the circularity of plastics, different recycling options have emerged in the past decade (in contrast to the current established End-of-Life (EoL) options for plastics like incineration (IC) with/without energy recovery and landfilling), which could play an integral role in the circular economy of plastics. The possible EoL options for plastics are shown in **Figure 1**, including different recycling possibilities as well as other recovery or disposal options that are currently in use.

The use and the magnitude of these EoL options to treat plastic wastes differ significantly between countries, which highlights the importance of considering a country-specific waste management infrastructure.[4] Moreover, the recyclability, as well as the resulting quality of recyclates, could be already determined in the product design phase due to the choice of additives, combination of materials as well as possibilities for disassembly.[5,6] Therefore, it is important to address the impacts of the production, use, and their EoL phases when designing plastic products.

V. Venkatachalam, M. Pohler, S. Spierling, L. Nickel, H.-J. Endres
Institute of Plastics and Circular Economy
Leibniz Universität Hannover
An der Universität 2, Garbsen 30823, Germany
E-mail: venkatachalam@ikk.uni-hannover.de

L. Barner
Centre for a Waste-Free World
Faculty of Science, School of Chemistry and Physics
Queensland University of Technology
2 George Street, Brisbane, QLD 4000, Australia

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/macp.202200046

DOI: 10.1002/macp.202200046

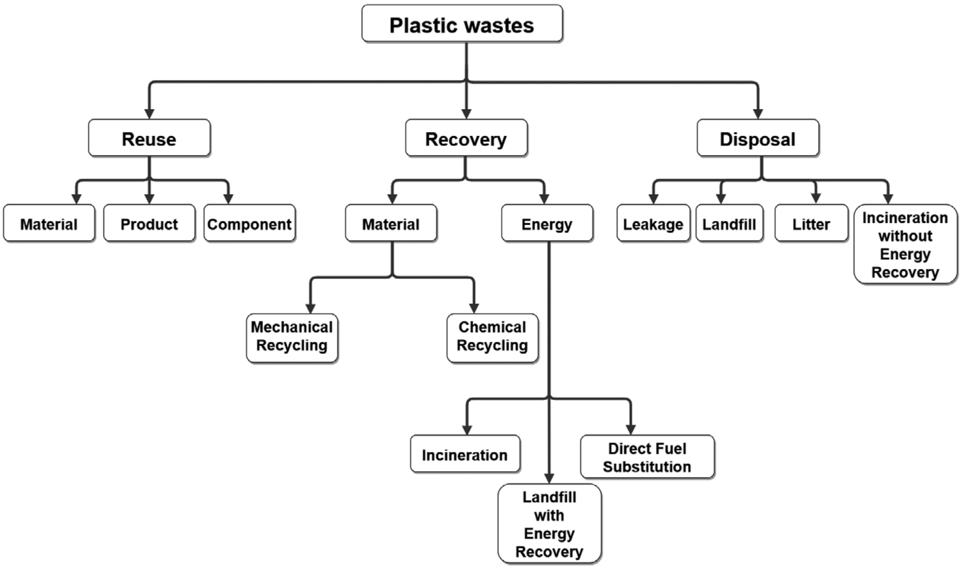

Figure 1. Overview of possible EoL options for plastics.

The concept of Design for Recycling (DfR) enables the inclusion of parameters of the product design in direct connection to its impact on the recycling potential and therefore tries to optimize and increase the recyclability of the products already in the design phase.[7] To enable a holistic DfR approach, not only the technical aspects but also the environmental aspects have to be quantified and included. A suitable methodology to assess the environmental impacts of products and technologies is Life Cycle Assessment (LCA) based on ISO 14040/44.[8,9]

LCAs quantify the environmental impacts of different products/technologies as well as allow a sound comparison between them. The environmental performance of the EoL options can be analyzed and quantified with the help of LCA. Using LCA, the environmental impacts of the product system across the value chain can be evaluated and the factors that influence the type of EoL option chosen for different plastic products can be better understood.

To allow for an environmental improvement of these technologies as well as setting the focus on the most environmentally beneficial pathways, an overview of the current environmental impacts of EoL options for different plastic types is necessary. Therefore, the current study aims to establish a comprehensive overview of the impacts of different recovery options for plastics. Although some review studies on LCA and EoL options of plastics have already been published in the past ten years, these reviews focused their research on certain plastic types, EoL options, geographical regions, impact categories, or the methodological aspects of LCA.[10–16] This current study tries to analyze as many plastic types and their different EoL options across the world as possible along with the different impact categories.

Based on the environmental impacts analyzed from this review, a preliminary Circular Footprint (CF) for plastics in different regions of the world corresponding to their recycling infrastructure is calculated. Using these results, DfR strategies are identified, which will support the designers and manufacturers during the material selection for their products as early as during the design phase and understand the usage (or disposal) and the environmental impacts of their plastic products when used across the world.

1.1. Status Quo – Global Plastic Waste Management

In 2020, it is estimated that 367 Mio t of plastics were produced worldwide.[17] The main plastics producing countries are China (32%), countries of the North American Free Trade Agreement (NAFTA), that is, United States of America (USA), Canada, and Mexico, (19%), other countries of Asia (17%), and Europe (15%).[17] In 2010, the countries that generated the largest amount of plastic waste (which is an indication for plastics consumption) were China, the USA, Germany, and Brazil.[18] It should also be mentioned that oil—a non-renewable resource—is consumed in the production of plastics as material feedstock and as fuel for the production process (in a ratio of approximately 1:1).[19] In 2014, approximately 6% of the global oil consumption was used for plastic production. As plastic production is increasing worldwide, the percentage of oil consumption will increase as well. However, this could be counterbalanced by increased use of recycled plastics as material feedstock and renewable energy sources for plastics production.

As described in Figure 1, a range of options exists for the formal management of plastics at their EoL, that is, recycling (including export for recycling), IC (with and without energy recovery), and landfill (LA). Unfortunately, mismanagement of plastic waste is prevalent in many parts of the world resulting in littering, illegal dumping, uncontrolled burning, and deposition in LAs, which in turn contribute to marine plastic pollution and landscape pollution with detrimental effects on the ecosystems. The availability of plastic waste management options strongly depends on the socio-economic status of the respective country. In general, the Global North (Including Western Europe, North America, Australia, New Zealand, Japan, South Korea, and

Singapore) has an efficient infrastructure for the management of plastic waste (under the assumption that LA and IC are considered efficient which reflects more of a linear than a circular economy).

In 2020 in the 27 EU countries, the United Kingdom, Norway, and Switzerland, 29.5 Mio t of post-consumer waste plastic was collected. Of these 23.4% were landfilled, 42% were used for energy recovery, and 34.6% were recycled.[17] In 2018, plastic waste generation in the USA resulted in 35.7 Mio t, of which 3 Mio t were recycled (8.7% recycling rate), 5.6 Mio t were incinerated, and the majority (27 Mio t) was landfilled (75.6%).[20]

Australia generated 2.54 Mt of plastic waste in 2018–19, of which almost 13% was recycled and a little less than 3% was incinerated with energy recovery. 85% of plastic waste was deposited in LA.[21]

In the Global South, that is, low-to-middle-income countries, adequate formal infrastructure for plastic waste is scarce and plastic waste is often mismanaged. Jambeck et al. describe how the lack of adequate plastic waste management systems in developing countries contribute to plastic waste entering waterways and oceans in significant amounts leading to ocean pollution by plastics and the creation of large marine garbage patches.[18] Therefore, reducing the amount of mismanaged plastic waste by establishing formal waste management systems (ideally recycling systems) in developing countries and a reduction of the use of unnecessary single-use plastics is very important. However, the impact of the informal waste recycling sector-which refers to the waste recycling activities of scavengers and waste pickers-in developing countries should not be underestimated and must be accounted for when formal waste management systems are established.[22]

A report on plastic waste management published in 2019 estimated the market size of plastic waste management at USD 33.1 billion for 2019 and predicts a growing market on one side due to rapid industrialization, rising urbanization, increased use of plastics, and on the other side due to an increasing conscience of the detrimental impacts of incorrect waste management of plastics.[23] Especially, in the Asia Pacific region the plastic waste management market is predicted to grow.

In addition, the export of plastic waste from developed countries (with adequate waste management systems) to developing countries (with often inadequate waste management systems) significantly adds to the mismanagement of waste and ultimately marine plastic pollution. For example, China will release approximately 1.3 Mio to 3.5 Mio t. of plastic waste into the ocean per year while developing an efficient waste management infrastructure. Brooks et al. report that nine of the top ten plastic waste exporting countries (i.e., Hong Kong, USA, Japan, Germany, UK, Netherlands, France, Belgium, and Canada) are high-income countries, except for Mexico which is an upper-middle-income country and ranked 5th.[24] Some of these high-income countries also import plastic waste, however on a much lower percentage.

Therefore, recycling plastics, that is, the recovery of plastics after their use so that the material does not leave the economy, is one of the important components in the transition from a linear to a circular economy. However, recycling plastics faces a couple of challenges. First, there is the issue of collecting plastic waste in a simple but sufficient way that keeps contamination and transport costs (including the carbon footprint of transport) low. Second, segregation of plastic waste before (re-)processing is essential, but often hampered by the use of different types of plastics in the same product or difficulties in identifying the type of plastic used. In addition, the additives used in plastic products can be challenging for the recycling process. Third, sufficient infrastructure for collection transport, segregation, and material production needs to be available. Finally, all these actions need to be performed in an economically viable and sustainable fashion.

Policies, national laws, and international treaties are playing an important role in addressing the mounting problem of plastic consumption and waste. Johnson et al. analyzed the importance of transnational regulation for the production, consumption, and disposal of plastics and identified three significant deficiencies, that is, failure to consider plastics in terms of environmental justice and human rights, insufficient plastics prevention, as well as the role of law in reinforcing plastics production and consumption.[25] Nevertheless, more and more countries ban or restrict the use of plastics, especially the use of single-use plastics (i.e., plastic bags, straws, stir sticks, cutlery, plates, ...) and microbeads in cosmetics and cleaning products.[26] Among the countries that have or are planning to ban single-use plastic items are Australia, Canada, China, Europe, India, Kenya, UK, some states of the USA, and Zimbabwe.[27] China's ban on plastic waste imports had a significant effect on the global plastics market shifting the waste exports to other countries—namely Malaysia, displacing an estimated 111 Mio t of plastic waste by the year 2030 and triggering waste export bans, for example, Australia.[24,28] Therefore, these complexities across the value chain of plastics and the fate of the plastic products after use must be considered by the manufacturers at the design stage. Also, exporting the finished plastic products or the plastic wastes to the countries, which lack the basic infrastructure to collect and recover plastics after use let alone recycle these materials comes with the high risk of losing the non-renewable resources from the value-chain. This also results in a major decrease in the resource efficiency of the whole product system. From the status quo, it can be seen that not all the plastic wastes that are produced by the countries are recovered and recycled locally, but a part of these wastes are exported to other countries. This situation makes it even more difficult to quantify the environmental impacts of disposing these plastic wastes as the manufacturers and users seldom acquire data from the countries to which wastes are exported.

2. Experimental Section

2.1. Bibliometric Analysis

A comprehensive literature review was performed as a part of the current study to identify the DfR strategies and quantify the environmental impacts of the different EoL options of plastic wastes. This review mainly analyzed the LCA studies of different EoL options of plastic wastes that were conducted by researchers across the world. The time frame of the literature review was set from 2010 to 2021 keeping in mind factors like the improvement in collection, sorting, and mechanical recycling (MR) of plastic wastes, emergence of new plastic types, new EoL options in treating the plastic wastes, increase in the rate of consumption of plastic materials, and generation of plastics wastes across the world over the past decade.

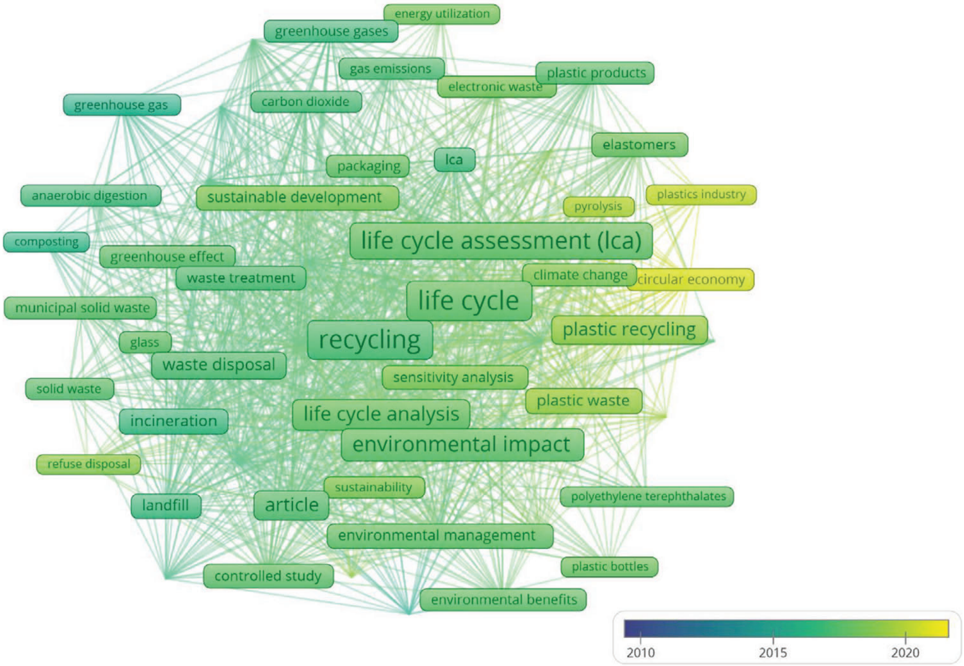

Figure 2. Co-occurrence of keywords for a set time period (2010–2021) by a bibliometric analysis based on the title and abstract search from 416 studies using VOSViewer.

Before conducting the literature review on LCA of the different EoL options, bibliometric analysis on the co-occurrence of keywords for the set time frame was performed and visualized with the help of VOSViewer.[29] For this visualization, a basic search with the keyword combination of "Plastics" AND "LCA" AND "Recycling" for the timeframe 2010 to 2021 was done with the help of the search engine Scopus, which was the largest abstract and citation database of peer-reviewed literature.[30] The terms "End of Life" or other EoL options like "Incineration" and "Landfill" were not included in the search as most of the titles and abstracts of the studies in the first screening did not have these keywords. If all these studies discussed EoL options, it was more in the direction of treatment or disposal of plastic wastes. In the case of IC, the titles and abstract discussed the thermal recovery or recycling of plastic wastes.

For the defined combination of search terms mentioned above, 416 results were found which were then exported along with the year, title and abstract into VOSViewer. The VOSViewer software helps in creating maps on the co-occurrence of the keywords, authorship, and citations based on the bibliographic data provided to the software. For this study, the possible co-occurrence (refers to the occurrence of the same keyword in other publications) between the different keywords over the time period was counted and the links between the keywords (co-occurrence) were visualized in the form of a map. Increase in the occurrence of the same keyword in different studies increases the relevance of these keywords (thereby the link strength between the keywords), which were then linked to the other keywords with a similar number of co-occurrences in these studies. The visualization of the co-occurrence of keywords in the abstracts and titles for the given search combination over the time frame is shown in **Figure 2**:

In total, there were 60 co-occurring keywords linked to each other with the threshold for each keyword set to occur at least more than 20 times. Due to the weak link strength of some of the keywords, not all the keywords could be displayed in Figure 2. For the sake of simplicity and better understanding, keywords like "journal" and "peer review" were not considered in this visualization despite having a large number of co-occurrences.

From Figure 2, it can be seen that the terms relevant to LCA like "environmental impact" (159 occurrences), "life cycle" (236), "life cycle analysis" (Some publications tend to use this term instead of LCA) (131), and "life cycle assessment" (195) occupied the majority of co-occurrences among different publications along with the terms "waste disposal" (78), "waste treatment" (52), and "waste management" (134) that were common to all of these studies. Apart from the conventional "recycling" (219) of plastics, LCA for other EoL options like "composting" (20), "anaerobic digestion" (important EoL options for bio-based plastics) (22), and pyrolysis (21) have also gained attention over the past few years. To understand the environmental impacts of products from different materials, comparative LCAs have also been done between plastics and other materials like "glass" (22). Many LCA studies focus on specific types of plastic products ("plastic bottles" (20)), sector ("electronic wastes" (25), "packaging" (34), material type ("Polyethylene Terephthalate" (21), "Polymers" (25) "Elastomers" (49)), impacts ("Gas emissions" (27), "Greenhouse gases" (38), "carbon dioxide" (27)). There was also an increase in the presence of terms like "circular economy" (coincides with the circular economy policy initiatives across the world to conserve resources thereby mitigating climate change (39)),[31–33] "sustainable development" (coincides with the introduction of SDGs)[34] (53), and most likely the potential or the relevance of it in the "plastics industry" (21) in the last few years.

Table 1. Search categories and terms used for the literature review.

Category 1	Category 2	Category 3
End-of-life Options	Plastics	Mechanical Recycling
End-of-life Treatment	Polypropylene	Chemical Recycling
Life Cycle Analysis	Low Density Polyethylene	Direct Fuel substitution
Life Cycle Assessment	High Density Polyethylene	Pyrolysis/Hydrolysis/Gasification
Sustainability assessment	Polyethylene terephthalate	Waste to Energy
Waste management	Polystyrene	Incineration/Combustion
Disposal	Polyvinylchloride	Refuse Derived Fuel
Carbon footprint	Polyamide	Energy Recovery
Plastics and circular economy	Mixed plastics wastes	Landfill/Disposal
Environmental impact	Municipal Solid Wastes	Reuse

However, there were not many co-occurrences of terms like "Product design", "Ecodesign", or "Design for recycling" among the studies, which highlights how little to no importance was given to the optimization and change of the environmental performance of the plastic products in the conducted studies through product or process (re)-design. This bibliometric analysis served as a basis for the literature review that was conducted on the LCA studies of different EoL options.

2.2. Literature Review

For the literature review of the LCA studies, three different categories of search terms have been created thereby including different aspects of treating the plastic wastes. The combination of keywords from all of these three categories was subsequently used for the screening analysis of the literature. The first category included the set of general search terms like "Waste Management, 'Disposal", "Life Cycle Assessment", "Sustainability Assessment", and "Carbon Footprint", which were then combined with the second set of categories that consists of different types of polymers and plastics wastes like Polypropylene (PP), Polyethylene (PE), mixed plastic wastes (MP), and municipal solid wastes (this search term becomes relevant in the countries where Single Stream Plastics (SSP) recycling were not prevalent due to the inadequate infrastructure to sort the wastes into different fractions).

These two sets of search categories were then combined with the third set of search term category, which deals exclusively with the different types of EoL options like MR, chemical recycling (CR), IC, and LA. With these search term categories, it was easier to find duplicates during the literature review thereby getting specific literature, which will then be screened through a set of assessment criteria. **Table 1** shows an overview of the terms in the three categories. Since the scientific publications on this topic were mainly available in English, the search terms were also chosen in English and the literature results in other languages were not considered for this review. The timeframe for the literature review was the same one as for the bibliometric analysis, which was from the year 2010 to 2021.

Apart from combining the search terms from different categories, a parallel search on the already existing review studies regarding LCA studies of EoL options of the plastic (both conventional and bio-based) wastes was conducted and the studies cited in those review studies were also screened as a part of this literature review. As many as 785 documents (including 35 additional documents from the parallel search and review studies) were found as a part of the initial literature search on Scopus. However, there were some duplicates found among these two searches, which were then excluded to result in 762 publications that had to be screened. Some of the publications were also excluded because of the inaccessibility of these documents during the research period. The authors, then, based on their expert estimation excluded some of the records after reading their respective titles and abstracts. As many as 531 studies were excluded at the end of this screening process, which then resulted in the thorough screening (reading the complete paper) of 231 studies. To include the essential LCA studies for the review and increase the comparability of the results from the LCA, a set of screening criteria was defined.

For the LCA studies to be included in the final review, they must comply with the following criteria: 1) Only LCA studies reporting the EoL options of conventional plastics were considered, that is, LCA studies involving the EoL options of composites and fibers were not considered; 2) LCA studies must follow the attributional approach, that is, LCA studies with the consequential approach were not considered as the results from these approaches were not comparable with the attributional ones; 3) LCA studies reporting the mixed plastic blends (For example: PC-ABS blends) were not considered; 4) LCA studies should focus on the EoL options. If not, they should have atleast separately presented the results for the respective EoL options they used for their product system; 5) EoL options in the LCA studies were considered separately and mixed scenarios were not considered, that is, LCA studies with the combination of treating the plastic wastes like 50% Recycling, 35% IC, and 15% LA were not considered as it would be difficult to identify the individual contribution of the EoL option towards the total impacts. The LCA studies should have presented their Life Cycle Impact Assessment (LCIA) results (also known as environmental impacts) for 100% Recycling or 100% IC or 100% LA. However, LCA studies that treat the residues of the plastic wastes with other EoL options were still included in the review; 6) absolute values of LCIA results should be available; 7) Only the midpoint indicators of the LCIA results were

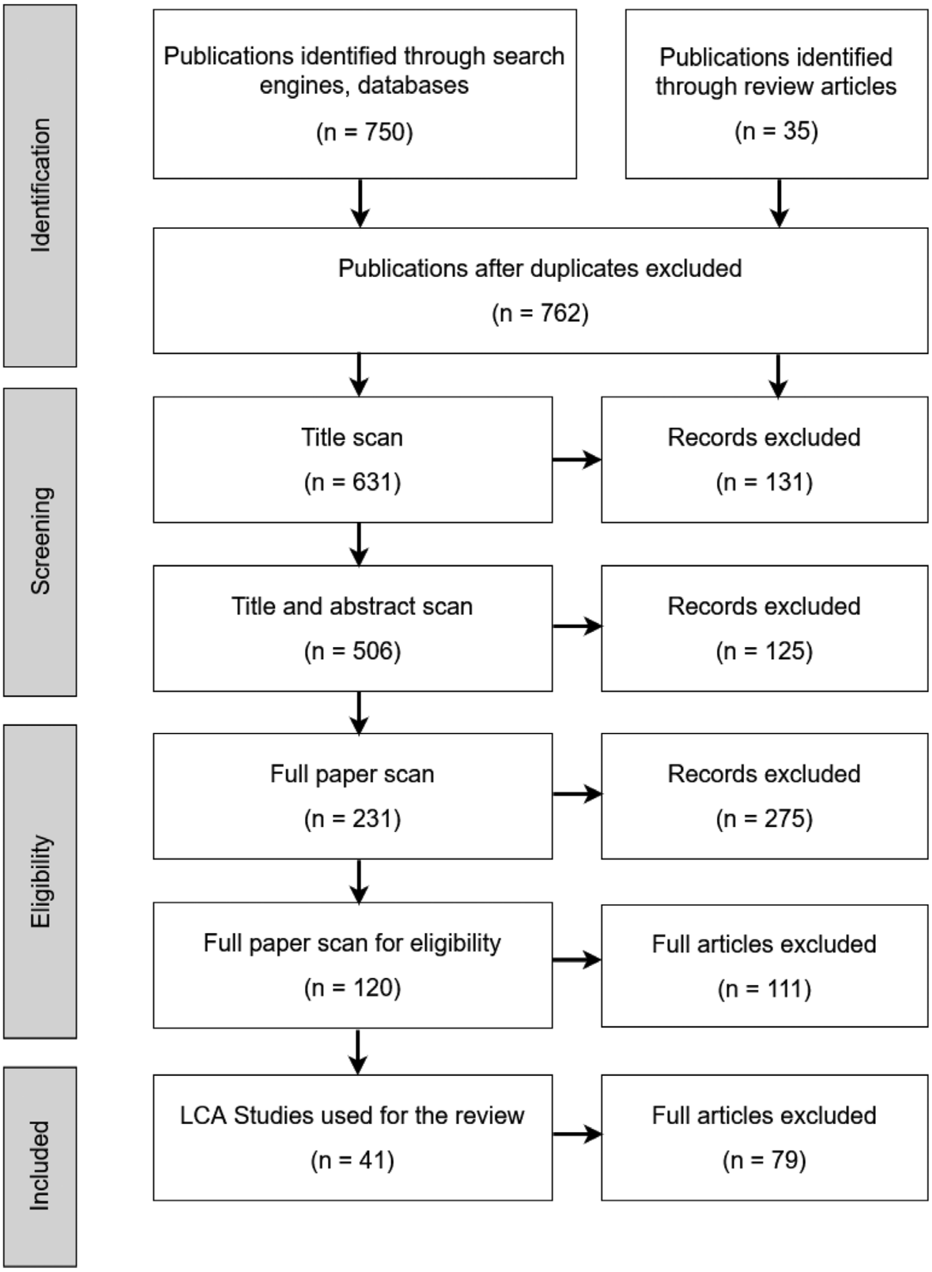

Figure 3. Screening analysis for the literature review. Reproduced under terms of the CC-BY license.[35] Copyright 2009, the Author(s). Published by PLoS Medicine.

considered; 8) Only the LCIA results from the studies that had either cut-off or avoided burden approach as the methodological approach to quantify the impacts of the product system at the EoL were considered.

Based on these screening criteria, a full paper scan was performed and out of 231 studies, 41 LCA studies were taken for the calculation of average environmental impacts of different types of plastic wastes, which were then used for the calculation of CF and subsequently for the identification of DfR strategies. The LCIA results and the average impacts of different EoL options will be discussed in detail in Section 3.1 and the information extracted from LCA studies are shown in Table S1, Supporting Information. The complete list of all the 165 scenarios along with the extracted information are shown in Table S2, Supporting Information. The screening analysis for the literature review of LCA studies of the EoL options of plastic wastes is shown in **Figure 3**:

Despite these 41 LCA studies having different functional units (the reference unit for quantifying the environmental impacts of the product system, that is, environmental impacts of 1 plastic bottle, 1000 tons of municipal solid wastes, which describes the function of the product system with the physical dimensions for the end product under study), the LCIA results were then calculated per kg of plastic waste and were then used for the calculation of the CF.

The EoL options considered for the literature review are: Reuse (R), MR, CR, Direct fuel Substitution (DS), IC, LA, and LI. As mentioned in Section 1, EoL options like pyrolysis and gasification were included as a part of CR. Also for the purpose of showing the main EoL options in the literature review, there was no distinction made between IC with or without energy recovery and LA with or without energy recovery in **Table 2**. However, during the calculation of the average environmental impacts of different plastic types, distinction was made between the EoL options with and without energy recovery.

The type of polymers/plastic wastes that were considered for the literature review are: High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), PE, PP, Polyethylene Terephthalate (PET), Polystyrene (PS), Polyurethane (PUR), Acrylonitrile Butadiene Styrene (ABS), Polyvinyl Chloride (PVC), Poly (Methyl Methacrylate) (PMMA), Polyolefine (PO), and MP. The considered LCA studies along with the choice of EoL options and the polymers studied in the respective studies are listed in Table 2. The individual scenarios resulting from analyzing the EoL options of each plastic type across these 41 studies are shown in Table S2, Supporting Information.

Despite setting different criteria to ensure the quality of the studies analyzed in this literature review, there were some limitations in the literature review, which must be considered when interpreting the LCIA results and the subsequent calculation of preliminary CF of different countries. The limitations of this literature review were:

- Almost all of the analyzed LCA studies used predominantly secondary data from LCA databases, previously conducted LCA studies, and literature. The data quality and the corresponding results can be hugely improved with the availability of primary data in recycling plastic wastes across the world
- Average environmental impacts were calculated from the literature review for treating every plastic-type with different EoL options. However, between the countries where the LCA studies were conducted, the recycling or the IC infrastructure was never the same and therefore the substitution potential of the recyclates to the virgin plastic differs from region to region. The use of recovered energy and steam by burning the plastic wastes and their heating value also differed from city to city. The current methodological approach of calculating the preliminary CF for treating specific plastic wastes can be applied in future studies for specific regions across the world (Region specific LCA of EoL options of plastics wastes along with the corresponding data on their use, recovery, and disposal)
- Even though PE as a plastic type was considered for the literature review, the preliminary CF was calculated based on the HDPE, LDPE share of plastic production and environmental impacts of disposing them in different countries

The results of the literature review along with the average environmental impacts of EoL options of different plastics from the review are discussed in detail in Section 3.1. These average environmental impacts calculated from the literature review for different EoL options were then used for the calculation of CF, which quantifies the environmental impacts of the product system based on the quality, market mechanisms, and the recovery/disposal rate of the plastic wastes in the product system. The average environmental impacts of the EoL options of plastic wastes were analyzed separately for cut-off and avoided burden approaches, the two most common modeling approaches for accounting the environmental impacts of recovered materials during the EoL phase of plastics.

In the case of avoided burden approach, the environmental impacts were allocated in such a way that the primary system (that produces the plastic wastes for recovery) takes the credits for the wastes that were generated in their product system with an assumption that these wastes (secondary materials) were recovered, recycled and substitute the primary (virgin) materials in the second system. So the impacts of not producing a virgin material due to the substitution were allocated as credits for the first system.

In the case of cut-off approach, the product system (both the producer and receiver of wastes) never takes credits and only the direct impacts caused by each system were calculated. In the case of second system, the one that receives the recycled materials, neither credits (for the secondary material) nor the burdens (impacts of producing the products) were assigned and only the impacts caused by treating these products were calculated and assigned to the system in the cut-off approach. The environmental impacts from these approaches were then used in Circular Footprint Formula (CFF) and the CF of different product system was calculated, which is discussed in detail in Section 3.3.

As this study not only involves the calculation of average environmental impacts of the EoL options, but also calculates preliminary CF and identifies DfR strategies for these plastic wastes, a literature review was performed for the studies that have already been published in the field of CFF and DfR. The CFF was introduced by the European Commission in order to account the burdens and credits associated with the recycling, energy recovery, and disposal processes as well the use of secondary (recycled) materials while calculating the environmental footprint of the product system.[76,77]

As the CFF was introduced recently as a part of the Product Environmental Footprint (PEF) methodology, literature related to this formula and the publications that dealt with this formula were also identified. As it was a relatively new approach to model the recycling of the product system, not many publications were identified. Schrijvers et al. evaluated how CFF has the potential to follow the consequential LCA approach as CFF also considers the market mechanisms of the secondary material (recycled material), which was consistent with the consequential LCA perspective.[78] Ekvall et al. analyzed the pros and cons of using CFF among other modeling approaches for recycling in LCA.[79] Ekvall et al. also discussed the effects of energy recovery on the calculation of CFF by using a case study of waste management of bio-based LDPE.[80] Bach et al. discussed the shortcomings related to the CFF among other aspects in the Product Environmental Footprint Category Rules (PEFCR) guide.[81] Eberhardt et al. used a set of different allocation procedures including CFF on circular building component examples to develop a new modeling approach from the results based on the existing approaches.[82] Mirzaie et al. also used CFF as one of the EoL modeling approaches for buildings, to achieve circular economy targets.[83]

Table 2. Overview of the 41 LCA studies, selected for the literature review.

Source	EoL Options							Polymers studied											
	Reuse (R)	Mechanical Recycling (MR)	Chemical Recycling (CR)	Direct Fuel Substitution (DS)	Incineration (IC)	Landfill (LA)	Litter (LI)	High Density Polyethylene (HDPE)	Low Density Polyethylene (LDPE)	Polyethylene (PE)	Polypropylene (PP)	Polyethylene Terephthalate (PET)	Polystyrene (PS)	Polyurethane (PUR)	Mixed Plastics (MP)	Polyolefine (PO)	Acrylonitrile Butadiene Styrene (ABS)	Polyvinyl Chloride (PVC)	Poly Methyl Methacrylate (PMMA)
Accorsi et al.[36]		**MR**			**IC**	**LA**					**PP**								
Al-Maaded et al.[37]		**MR**			**IC**	**LA**									**MP**				
Al-Salem et al.[38]		**MR**	**CR**												**MP**				
Arafat et al.[39]			**CR**		**IC**										**MP**				
Aryan et al.[40]		**MR**			**IC**	**LA**				**PE**		**PET**							
Bataineh[41]		**MR**						**HDPE**				**PET**							
Belboom et al.[42]					**IC**			**HDPE**											
Campolina et al.[43]		**MR**											**PS**				**ABS**		
Changwichan et al.[44]					**IC**						**PP**	**PET**							
Chen et al.[11]		**MR**								**PE**	**PP**	**PET**	**PS**				**ABS**	**PVC**	
Choi et al.[45]		**MR**			**IC**	**LA**			**LDPE**										
Choudhary et al.[46]		**MR**										**PET**							
Civancik-Uslu et al.[47]		**MR**	**CR**		**IC**				**LDPE**		**PP**		**PS**			**PO**			
Clauzade et al.[48]	**R**	**MR**		**DS**										**PUR**					
Demetrious et al.[49]			**CR**		**IC**	**LA**									**MP**				
Dong et al.[50]					**IC**	**LA**									**MP**				
Franklin Associates et al.[51]		**MR**						**HDPE**			**PP**	**PET**							
Galve et al.[52]		**MR**									**PP**								
Gear et al.[53]					**IC**	**LA**													
Gironi et al.[54]		**MR**			**IC**	**LA**						**PET**							
Horodytska et al.[55]		**MR**			**IC**				**LDPE**										
Hossain et al.[56]	**R**	**MR**		**DS**	**IC**	**LA**									**MP**				
Hottle et al.[57]		**MR**				**LA**		**HDPE**	**LDPE**			**PET**							
Iribarren et al.[58]			**CR**		**IC**	**LA**				**PE**									
Jeswani et al.[59]					**IC**	**LA**									**MP**				
Jeswani et al.[60]			**CR**	**DS**	**IC**										**MP**				
Khan et al.[61]					**IC**										**MP**				
Khoo et al.[62]					**IC**	**LA**					**PP**								
Khoo et al.[63]		**MR**	**CR**		**IC**										**MP**				
Kikuchi et al.[64]			**CR**		**IC**														PMMA
Lim et al.[65]					**IC**	**LA**							**PS**						
Martin et al.[66]		**MR**			**IC**	**LA**						**PET**							
Nakatani et al.[67]		**MR**	**CR**		**IC**	**LA**						**PET**							
Papong et al.[68]		**MR**			**IC**	**LA**						**PET**							
Sangwan et al.[69]						**LA**		**HDPE**											
Santos et al.[70]		**MR**													**MP**				
Simon et al.[71]		**MR**			**IC**	**LA**						**PET**							
Tratzi et al.[72]		**MR**									**PP**								
Wang et al.[73]			**CR**												**MP**				
Zaman et al.[74]			**CR**												**MP**				
Zhou et al.[75]					IC	LA									MP				

Table 3. Literature review on DfR.

Source	Design aspect discussed
Huang et al.[84]	Impact factors of sustainable design and development of plastic molds
Almeida et al.[85]	Material selection for beverage packaging
Foschi et al.[86]	Integrated decision-making process in packaging redesign
Alpizar et al.[87]	Policy instruments for decision-making to curb marine litter
Sherwood et al.[88]	Recirculation and sustainable product design for bio-based products
Vogt et al.[89]	Redesign polymers and key challenges for advancement of plastic recycling
Leal et al.[90]	Indicator based product design approach to improve circular economy
Antonopoulos et al.[91]	Factors affecting the recycling of post-consumer plastic packaging waste
Löw et al.[92]	Guidelines and implementation of DfR in plastics
Mendes da Luz et al.[93]	Methodology to integrate LCA in the product development process
Civancik Uslu et al.[94]	Applying LCA and eco-design strategies to understand the environmental profile
Lewis et al.[95]	Strategies for sustainable packaging design
Sampaio et al.[96]	Redesign of products based on user needs
Vanegas et al.[97]	Metric to quantify ease of disassembly of products
Navajas et al.[98]	Eco-design and LCA to reduce the environmental impacts of an industrial product
Flizikowski et al.[99]	Design requirements for the shredding process in recycling polymers
Berwald et al.[100]	Design for circularity guidelines for electrical and electronic equipments
Du Bois et al.[101]	Attributes of recycled plastics influencing customer's perception of sustainable product

In the case of DfR, search terms like “Ecodesign”, “Design for Sustainability”, “Design for Recycling”, and “Design for environment” were given in order to find the relevant publications in this theme for the defined timeframe. Even though there were more than 1400 results for the given search combination, only some of the studies were relevant to the design or redesign approaches for plastics/polymers and plastic wastes to increase the circularity. Although some of these studies did not explicitly mention that these strategies were for ecodesign or DfR, they were still considered as they strive towards the increase in the resource efficiency and circularity of the product system, which was one of the strategies of ecodesign/DfR. The review of all these studies was not within the scope of this paper. The studies that were considered for identifying DfR strategies in this paper and the aspects they have considered to increase the resource efficiency/circularity of the plastic products are shown in **Table 3**.

2.3. Method to Calculate the Circular Footprint on Global Scale

To calculate the environmental impacts of the recycling, IC, and disposal of plastic products after manufacture along with the production of virgin materials, CFF was used in this study. CFF also takes into account the market mechanisms and quality of the recycled materials not only used in the production processes but also at the EoL of the product system to understand the upcycling/downcycling effects of the recycled materials. The different components of the CFF are:

- Primary production – Environmental impacts in the production of the primary (virgin) input
- Secondary production – Environmental impacts of the secondary (recycled) material input
- Recycling at the EoL – Environmental impacts of the recycling process
- IC – Environmental impacts of the IC process with energy recovery
- Landfilling/Disposal – Environmental impacts of the disposal process without material/energy recovery

CFF was divided into three types that include all the above components: Material (Primary and secondary production, recycling at the EoL), Energy (IC), and Disposal (LA/Disposal). The sum of all the three components provides the total impact of the product system including its EoL options. The CF of a product system can be calculated based on Equations (1)–(4).[76]

Equation (1). Material component of the CFF which includes the environmental impacts of virgin material production, MR, and the recycling at the EoL along with the allocation factor, recycling share, and quality ratios of the recyclates to the primary product

$$\begin{aligned}\textbf{Material}: & \left(1 - R_1\right) E_\mathrm{v} + R_1 \times \left(AE_\mathrm{recyled} + (1 - A)\, E_\mathrm{v} \times \frac{Q_\mathrm{sin}}{Q_\mathrm{p}}\right) \\ & + (1 - A)\, R_2 \times \left(\mathit{ErecEOL} - \mathit{Ev} * \times \frac{\mathit{Qsout}}{\mathit{Qp}}\right) \qquad (1)\end{aligned}$$

Equation (2). Energy component of the CFF which includes the environmental impacts of IC processes along with the IC share, heating value and efficiency of steam, and energy recovery

$$\begin{aligned}\textbf{Energy}: & \ (1 - B)\, R_3 \times \left(E_\mathrm{ER} - \mathrm{LHV} \times X_\mathrm{ER,heat}\right. \\ & \left. \times E_\mathrm{SE,heat} - \mathrm{LHV} \times X_\mathrm{ER,elec} \times E_\mathrm{SE,elec}\right) \qquad (2)\end{aligned}$$

Equation (3). Disposal component of the CFF which includes the environmental impacts of disposal/LA and disposal share

$$\textbf{Disposal}: \left(1 - \mathbf{R}_2 - R_3\right) \times E_\mathrm{D} \qquad (3)$$

Equation (4). CFF developed as a part of PEF methodology of the European Commission

$$\textbf{CircularFootprint} = \textbf{Material} + \textbf{Energy} + \textbf{Disposal} \qquad (4)$$

A – Allocation factor of burdens and credits between supplier (primary producer) and the user of recycled materials
B – Allocation factor of energy recovery processes.
Q_Sin – Quality of the ingoing secondary material, that is, the quality of the recycled material at the point of substitution.
Q_Sout – Quality of the outgoing secondary material, that is, the quality of the recycled material at the point of substitution.

Q_P – Quality of the virgin material.
R_1 – Proportion of material in the input to the production but recycled from a previous system.
R_2 – Proportion of the material in the product that will be recycled (or reused) in a subsequent system.
R_3 – Proportion of the material in the product that was used for energy recovery at EoL.
E_{recycled} – Specific emissions and resources consumed (per functional unit) arising from the recycling process
E_{recEoL} – Specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL
E_v – Specific emissions and resources consumed (per functional unit) arising from the production of virgin material.
E_v^* – Specific emissions and resources consumed (per functional unit) arising from the production of virgin material assumed to be substituted by recyclable materials.
E_{ER} – Specific emissions and resources consumed (per functional unit) arising from the energy recovery process
$E_{\text{SE,heat}}$ and $E_{\text{SE,elec}}$ – Specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat, and electricity respectively.
$X_{\text{ER,heat}}$ and $X_{\text{ER,elec}}$ – The efficiency of the energy recovery process for both heat and electricity.
LHV – Lower heating value of the material in the product that was used for energy recovery.
E_D – Specific emissions and resources consumed (per functional unit) arising from the disposal of waste material at the EoL

In the current study, the components of the above formula were applied to the treatment of plastic wastes and subsequently, the CF of plastic waste management of different countries was calculated. The factors that were considered for the calculating the CF of different countries are: 1) Plastic demand in each country per year (which was used as the functional unit for calculating CF; 2) Market/consumption share of different plastics and the contribution of each of them in every country (For example: PE – 30%, PP – 25%, PET – 15%, PS – 5%, PVC – 5% Others – 20%); 3) How the plastic wastes were recovered/disposed (For example: 35% Recycling, 40% IC, 25% LA). Based on the literature review, average environmental impacts were calculated for different plastic types for the virgin material, recycling process with and without credits (avoided burden and cut-off approaches respectively), IC with and without energy recovery (different types of EoL options), and the landfilling of plastic wastes (it was assumed that the majority of LCA studies considering LA had calculated environmental impacts for their disposal processes without energy recovery). Some of the assumptions that were used for the calculation of CF for the plastic waste management in different countries were as follows:

- The allocation factor A was based on the market situation and demand for the recycled materials. If the market for recycled plastics was balanced (between production and supply) or unknown, it was assumed to be 0.5.[77] For this study, as the demand for recycled materials and its applications in different countries were unknown, it was assumed to be 0.5
- Even though some of the recycled plastics were reused for the same applications in some countries, there has always been widespread downcycling of recycled plastic wastes all over the world and that was why it was assumed that the recycled product will not be used as a secondary material input into the product system, that is, $R_1 = 0$
- Quality ratios of the incoming and the outgoing recycled materials, Q_{Sin}/Q_P, Q_{Sout}/Q_P to the product were taken from the literature for different plastic types.[102–104] If these ratios were not available for some plastic types, then the average quality ratios of all the available plastic types were taken into account
- The environmental impacts of the virgin plastics (per kg), E_v were taken from the literature review. Only the indicator Global Warming Potential (GWP) (which was one of the many impact indicators that quantifies the environmental impact "Climate Change") values were available widely in the literature for different plastic types and therefore was used for this study. The GWP in the production of 1 kg of different virgin plastics are shown in Table S3, Supporting Information
- Emissions and resources consumed in the recycling processes E_{recycled} were taken from the results of the LCA studies of different plastics (the plastic types as mentioned above) in the review which have modeled their recycling processes with a cut-off approach. It was assumed that the $E_{\text{recycled}} = E_{\text{recEoL}}$ (emissions and resources from the recycling process at the EoL). The average environmental impacts of recycling processes of different plastic types using cut-off approach are shown in Table S4, Supporting Information
- Emissions and resources consumed during the production of virgin material, assumed to be substituted by the recyclable material, E_v^* were taken from the results of the LCA studies of different plastics (the plastic types as mentioned above) in the review which have modeled their processes with an avoided burden approach. The average environmental impacts, E_v^* are shown in Table S7, Supporting Information
- The emissions and resources of IC and LA were taken from the results of the LCA studies of different plastics (the plastic types as mentioned above) for the EoL options IC with energy recovery and LA without energy recovery respectively. The allocation factor, B was assumed to have the default value of zero.[77] The average environmental impacts of IC and landfilling processes of different plastic types are shown in Tables S5 and S6, Supporting Information
- The share of recycling, R_2 and IC, R_3 were calculated based on each country's share of recycling and incinerating their plastic wastes. The heating value LHV, along with the emissions and efficiency of the energy recovery processes were assumed to be integrated with the LCIA results as most of the studies sourced their background data from the different commercial Life Cycle Inventory (LCI) data providers and therefore not calculated separately[77]
- The CF of each country was calculated based on the share of HDPE, LDPE, PP, PET, and PS in its production demand (which was taken as a functional unit) and their respective plastic waste management. The average impacts of all the plastic types from the review were used for the plastics type "Others", which includes PVC, PUR, ABS, and other thermoplastics. Plastic composition/market share was assumed for countries, where data was not available
- If the production demand data were not available for a country, annual plastic consumption or the plastic waste generation data were taken as functional unit

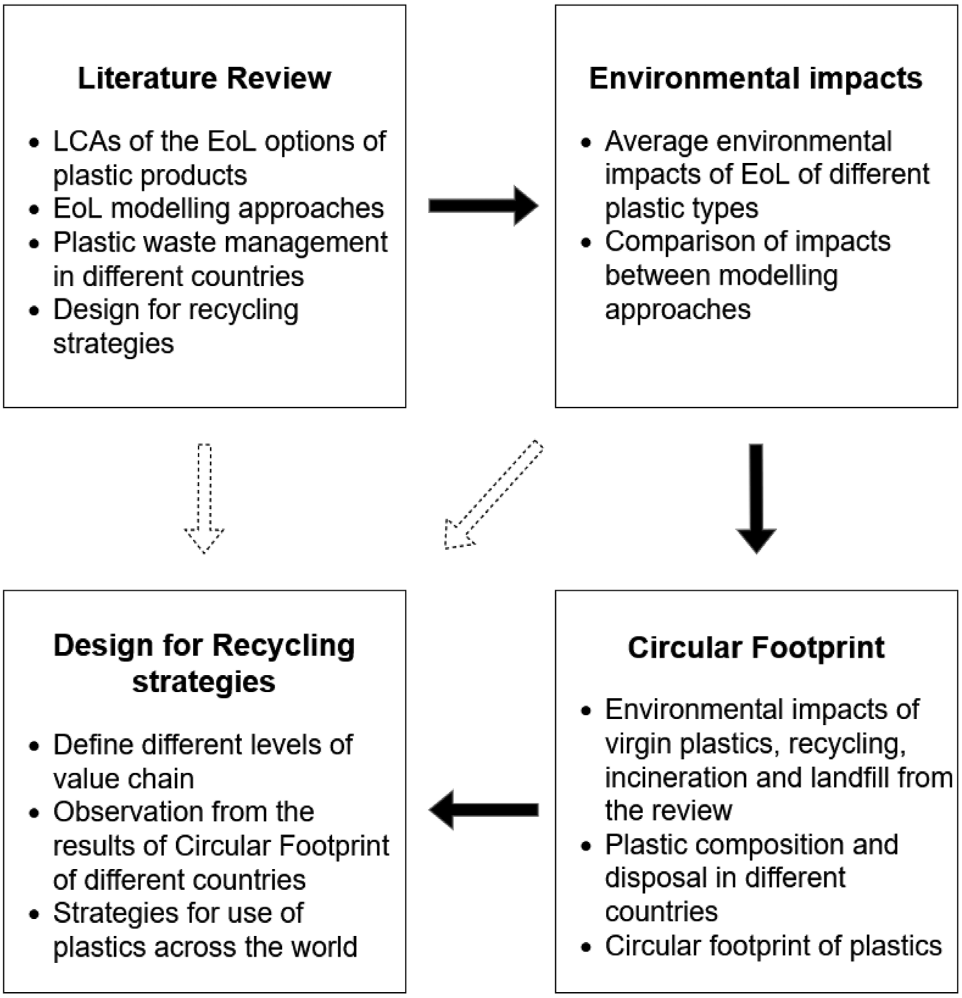

Figure 4. Methodological approach to identify the DfR strategies.

- The plastic production and consumption data were mostly assumed to be devoid of imports but in countries where imports exceed their own production, these were included in the annual plastic consumption
- As the CFF mainly deals with the accounting of the environmental impacts during the production and disposal of the product, impacts related to the processing and use phase of the plastic products were not considered in the calculation
- Discussion about the limitations, derivation, or the approach of this formula was not within the scope of this paper

Using the LCIA results of virgin plastics and different EoL options identified from the literature review, preliminary CF was calculated for treating plastic wastes in different countries. Based on these results, different DfR strategies were identified across different levels of the value chain. In order to better understand the relationship between the literature review and the DfR strategies, a calculation approach is visualized in **Figure 4**. The average environmental impacts of different plastics for the different EoL options were calculated with the data from the literature review and using these impacts and other assumptions, the CF for the plastic waste management systems in different countries can be calculated, which will help to understand the impacts of exporting plastic products and plastic wastes to other countries with a different recovery infrastructure when disposed. Based on not only these findings, but also the results of the literature review and the environmental impacts of EoL options of different plastics wastes (shown in dashed arrows), DfR strategies were identified for the production of plastic products.

3. Results and Discussion

3.1. Literature Review

As mentioned in Section 2, for the calculation of CF and identifying the DfR strategies for plastic wastes across the world, the average environmental impacts of different EoL options of different plastic wastes were calculated based on a comprehensive literature review. The environmental impacts of these EoL options are expressed as LCIA results, that is, the potential environmental impacts of the product system per functional unit. Based on different screening criteria, 41 studies were selected for the literature review of LCA studies of EoL options. However, there have been many instances of studies having multiple scenarios addressing different EoL options for the same plastic-type or different plastic-type for a particular EoL option. As each scenario produces an LCIA result, as many as 165 scenarios were found from the total of 41 studies and the LCIA results from all of these scenarios were analyzed and the average environmental impacts for each plastic type for the corresponding EoL options recycling (MR), IC with energy recovery and LA without energy recovery were used for the calculation of the CF for different countries.

As the methodological aspects in the LCA are subjective and always dependent upon the decision context and the defined system boundaries of the product system, it is important to analyze the different aspects of the LCA studies used in this literature review, which highlights the fact that the average LCIA results between different EoL options of plastics can only be cautiously used and might not always be the reflection of the real environmental performance of the assessed product system.

However, these results will provide an overview of the system boundaries, data quality, and value chains of the product systems. An overview of different aspect of the LCA studies in the review are discussed below and the detailed analysis of the different aspects of the literature review is shown in Tables S1 and S2, Supporting Information. The methodology to analyze the different scenarios of the LCA studies was based on Spierling et al., where the LCA studies of different EoL options of bio-based plastics were analyzed.[14]

3.1.1. Year of Publication

The timeframe for the review of LCA studies was set between 2010 and 2020. A significant increase in the number of publications from 2016 could be observed, which could be owing to the factors like introduction of different policy initiatives to curb single-use plastics on the national and international level, China's policy to ban the import of plastic wastes and the emphasis on the sustainable development and circular economy at the national and international level in the past few years. Nearly 83% of the LCA studies used for this review were published after 2013. However, the inventory data which were used for conducting these LCA studies did not correspond to this timeframe and therefore a change in the environmental impacts over the time should not be attributed to the year of publication because most of the publications use inventory data from other literature sources, which were published as early as 2004.

3.1.2. Types of Plastic

Though different plastic types were considered for this literature review (as mentioned in Section 2.2), only two types of plastic types contribute majorly to the total number of scenarios analyzed in this review and they were PET (46 scenarios) contributing to nearly 28% of the total scenarios, followed by the MP (45 scenarios) contributing to nearly 27% of the total scenarios. Other major plastic types that were discussed as scenarios in this review were PP (20 scenarios), PE (11 scenarios), LDPE (11 scenarios), PUR (9 scenarios), and HDPE (7 scenarios). From the plastic types, it can be seen how other plastic types like ABS, PVC, and PMMA were seldom analyzed in the LCA studies showing the state of recycling infrastructure to recover and treat these functional plastics. These aspects must be kept in mind during the material selection while designing plastics for recycling.

3.1.3. Type of End-Of-Life Option

As mentioned in Section 2.1, there were many EoL options, conventional and emerging technologies that were considered for this review, to gain an insight into the data quality and the environmental performance of these EoL options. It was assumed that the EoL options pyrolysis, gasification, and other forms of feedstock recycling were considered together as CR (apart from the CR wherever explicitly mentioned), wherein the plastic is converted back to the monomers, feedstocks, and other valuable materials.[105] The EoL options IC and LA with and without energy recovery were separately considered as EoL options to understand the difference in their environmental impacts across the LCA studies and the environmental impacts (LCIA results) of IC with energy recovery and LA without energy recovery were used for the calculation of the CF, apart from the MR. If the LCA studies involve plastic wastes being used as a substitute in cement or other building applications, the impacts of it were grouped under the EoL option “Reuse”. Under the EoL option “Direct fuel substitution”, scenarios that involve using plastic wastes as refuse-derived fuel (RDF) or solid recovered fuel (SRF) in waste to energy plants were covered.

No scenario was found for the EoL option “Litter” as there is not yet a scientifically established methodology to quantify environmental impacts of LI or leakage in LCA, which is one of the limitations of LCA although there have already been steps in the LCA community to develop littering indicators and quantify the environmental impacts of marine LI.[106,107]

From the analyzed scenarios, it was found that MR contributed to the majority of the analyzed scenarios (59 scenarios), followed by IC with energy recovery (34 scenarios) and LA without energy recovery (21 scenarios). The average LCIA results of these three EoL options were then used for the calculation of CF depending on the plastic share in each country and the percentage share of recovering/disposing plastic wastes in each country considered for this study. It was also found that only these EoL options are prevalent among all the countries for the disposal of plastic wastes and these were subsequently considered for the calculation of CF.

3.1.4. Life Cycle Impact Assessment Methods and Impact Indicators

The emissions resulting from the consumption of resources in the production and disposal of plastic products contribute to different environmental impacts, which are then classified as different impact categories like climate change, acidification, eutrophication, toxicity, and resource depletion. Each impact category is subsequently quantified as an impact indicator based on the choice of impact assessment method. For example: GWP is an impact indicator, which is used to quantify the potential impact of Climate Change and all these impact indicators are also known as LCIA results, which quantify the potential environmental impacts of the product system per functional unit.

Even though as many as 16 impact indicators were analyzed in this review (list of indicators considered for this study is shown in Figure S1, Supporting Information), due to the limited availability of most of the impact indicators among different studies and scenarios, only six impact indicators were considered to indicate the environmental performance of the EoL options of different plastic types. They were: GWP – 165 scenarios, Acidification Potential (AP) – 75 scenarios, Ozone Depletion Potential (ODP) – 51 scenarios, Photochemical Ozone Creation Potential (POCP) – 51 scenarios, Eutrophication Potential (EP) – 44 scenarios, Cumulative Energy Demand (CED) – 44 scenarios.

However, for the calculation of preliminary CF for treating plastics in different countries, only GWP was considered for this study, due to the lack of availability of indicator results for the EoL options of some of the plastic types. In the case of impact assessment method which characterizes the emissions of the product system in each process steps into respective impacts, as many as 9 different kinds of impact assessment methods were used, out of which CML (impact assessment method developed by the Institute of Environmental Sciences, Leiden University)[108] was the widely used impact assessment method to characterize the emissions into environmental impacts for the product system per functional unit.

3.1.5. Regional Scope & Geographical Representativeness of the Studies

To understand the geographical representativeness of the studies, the countries/continents where the EoL studies were conducted, were analyzed. It was found that the majority of studies come from Asia and Europe and it was interesting to see the limited number of LCA studies on the EoL options of plastics from Americas, Australia, and Africa. As many Asian countries like Malaysia, Thailand and Indonesia are the recipient of exported plastic wastes from the Global North and have an inadequate recycling infrastructure to recover these plastic wastes, the higher number of publications on this topic from these countries in Asia becomes relevant.

3.1.6. Technological (Laboratory/Industrial) Representativeness of the Studies/Scenarios

Out of 165 scenarios, only 10 of them discussed the EoL options of plastic wastes on a pilot scale and the rest of them were conducted at an industrial scale. The range of the LCIA results and the comparability of the results between the EoL options for different plastic types are influenced by the technological scale of the studies.

3.1.7. System Boundaries

The system boundaries refer to the process steps that are included in the calculation of the environmental impacts of the product system. In the case of the analyzed studies for the review, three different types of system boundaries were found among different scenarios. They are: 1) Cradle to Grave, 2) Gate to Grave, and 3) EoL. However, only LCIA results focusing on the EoL phase were taken from these studies so as to be consistent in comparing the results with each other.

3.1.8. Functional Unit

Functional unit quantifies the function of a product system and is defined according to the goal and scope of an LCA study. All LCIA results of the LCA study are then quantified based on the defined functional unit. In the case of this review, functional units were defined mostly on a mass basis, for example, 1 ton of plastic waste or 1 kg of waste PET bottle. If the studies would use different functional units, it would be difficult to compare the LCIA results/environmental impacts of different EoL options with each other. Therefore, for the sake of comparability and consistency, all functional units were converted to 1 kg so that all the corresponding LCIA results obtained from the review were used for the calculation of CF and the CF was then expressed as the impacts of the treatment of 1 kg plastic waste after use in different countries.

3.1.9. Credits

Credits are usually given to the product system if the end product resulting from the EoL is recovered in the form of a material or energy and is reused in the same/other product systems. Even though there exist different approaches to modeling recycling in LCA, for this review, two modeling approaches namely avoided burden and cut-off approaches were considered for the calculation of environmental impacts of the EoL options of plastics.[79] For the calculation of CF, results from both these approaches were needed and therefore the scenarios were separately identified and the corresponding results were used for the calculation of the CF.

3.1.10. Type of Plastic Waste

To understand how the examined plastics product was treated and the properties of the wastes, it is essential to know the type of products that were analyzed in the LCA studies. From the LCA studies in the review, it was found that all plastic wastes that were treated were post-consumer plastic wastes, that is, the wastes obtained after the plastic products were used by the consumers and there was no study that involved the recycling/disposal of the pre-consumer plastic wastes. It was also assumed that no closed-loop recycling was done across the studies but only open-loop recycling, wherein the products from one system are recycled and are used for the same/different applications in the second system.

3.1.11. Data Quality

The inventory data used for LCA of different studies, considered for this review were mostly secondary data, that is, data that are obtained from the literature, databases, and expert estimation rather than primary data, which are usually measured at the site

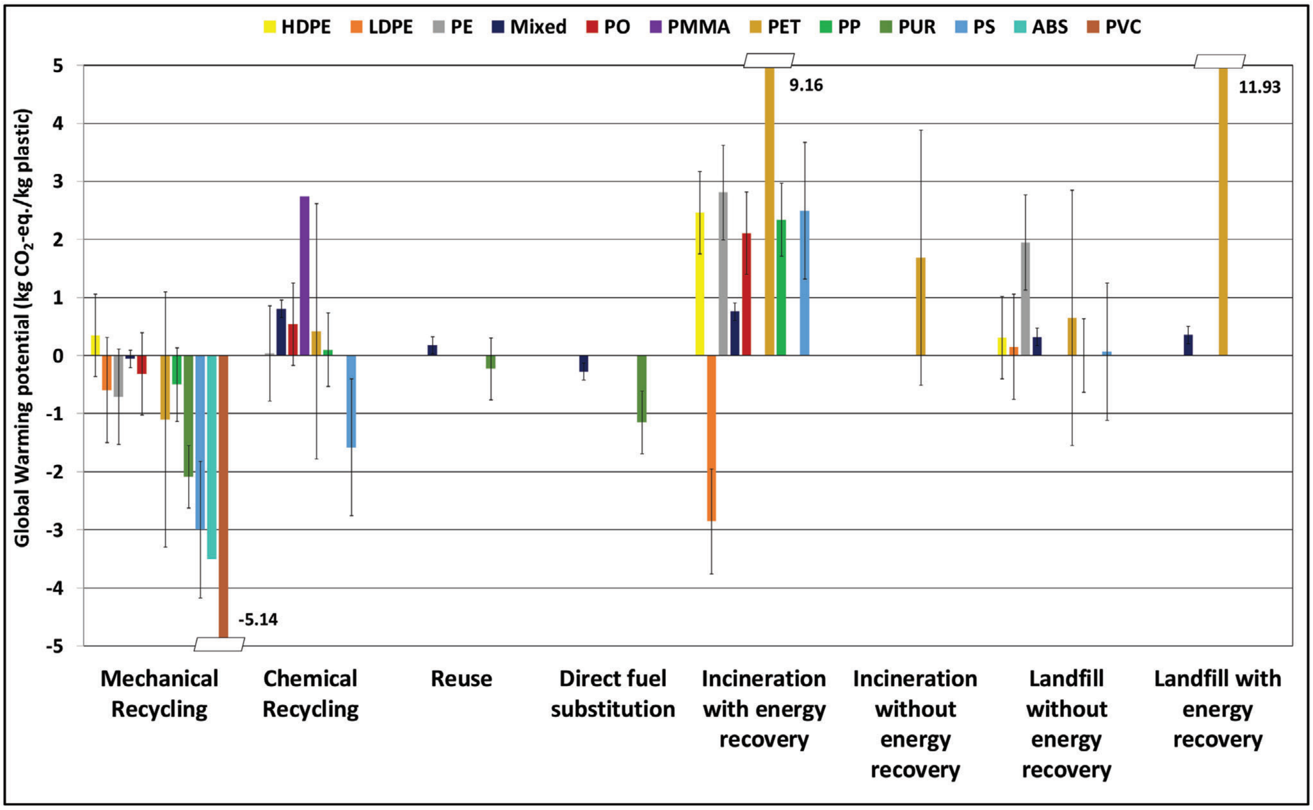

Figure 5. Average GWP of different plastic types treated by different EoL options using the avoided-burden approach. The error indicators refer to the range of GWP values that exist for treating the plastics in different EoL options. Negative values of GWP due to the accounting of credits in this modeling approach.

of the waste treatment plants. Apart from collecting data from literature sources, LCA studies also obtained their secondary inventory data in the form of datasets from different databases like GaBi, ecoinvent.[109,110] Even though it might be difficult to obtain the primary inventory data in each step of the value chain when recycling, data quality (primary data is always better than secondary data) does have an influence on the environmental performance of the EoL options. The higher the quality of inventory data sourced from the recyclers and sorting companies, the better it is for the designers to optimize the production of plastic products. The aspect of data availability should be integrated within the product system as early as during the design phase.

3.2. Impact Assessment – Results and Interpretation

After analyzing 165 scenarios from 41 LCA studies, the LCIA results were calculated for treating 1 kg of different plastic wastes for different EoL options. only six impact indicators were considered and the LCIA results were then calculated for both avoided-burden and cut-off approaches for all the possible EoL options. The GWP of treating 1 kg of different plastic wastes by different EoL options for avoided burden is shown in **Figure 5**. The results of other impact indicators for both approaches are shown in Supporting Information (From Figures S2–S14, Supporting Information).

The EoL options mentioned in Figures 5 and **6** are: MR, CR, Reuse (Re), Direct Fuel Substitution (DS), IC with Energy Recovery (IwER), Incineration without Energy Recovery (InoER), LA without Energy Recovery (LFnoER), and LA with Energy Recovery (LFwER). The plastic types that were considered for this review were already mentioned in Section 2.2. All LCIA results discussed in this study are expressed per kg of plastic wastes unless specified otherwise.

From Figure 5, it can be seen that the GWP of the MR of 1 kg of different plastic types (except HDPE, which is around 0.34 kg CO_2 eq.) have negative values, as in the avoided burden approach, the product system avails "credits" with an assumption that the secondary materials recovered from the system will substitute the production of virgin materials when recycled. The impacts of different plastic types for MR (apart from HDPE) are in the range of −0.06 to −5.14 kg CO_2 eq. Moreover, MR is the only EoL option where almost all of the considered plastic types were covered, followed by IC with energy recovery and LA without energy recovery. For CR, GWP was in the range of 0.04 to 2.74 kg CO_2 eq. except for PS, wherein the GWP had a negative value of −1.58 kg CO_2 eq.

CR is one of the emerging technologies in the recovery of feedstocks from plastic wastes. Most of the GWP results of the plastic types in CR have a positive value due to the fact that the environmental impacts of treating the plastic by CR outweighed the credits of the recovered materials which might substitute the primary feedstocks (virgin monomers).

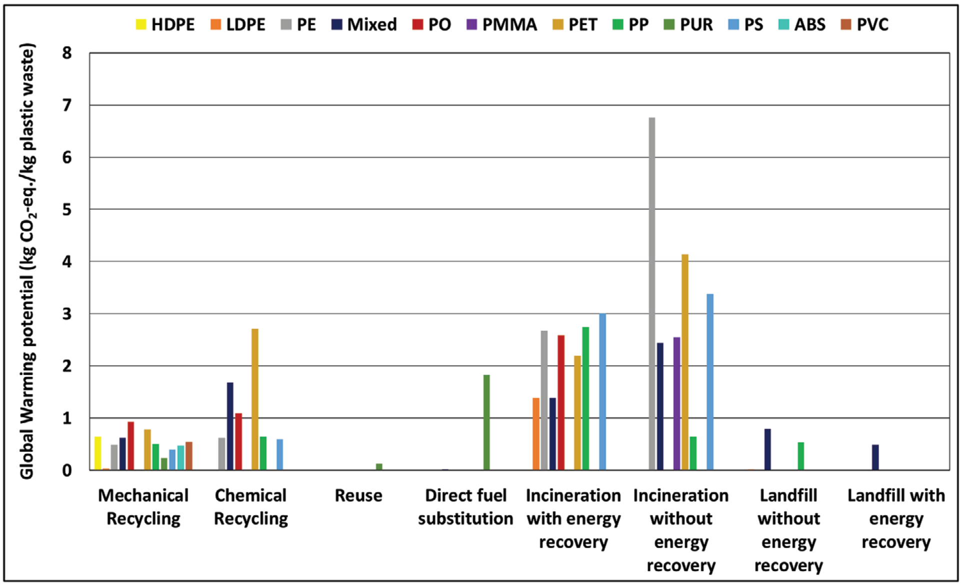

Figure 6. Average GWP of different plastic wastes treated by different EoL options using cut-off approach.

In the case of Reuse, GWP values were available only for Mixed plastics and PUR and in these studies, Reuse was more of a substitution of plastic wastes in different applications like synthetic turfs. However, the impacts of transporting and processing them were taken into the total environmental impacts. Similar to reuse, for Direct Fuel Substitution, GWP was available for studies that considered Mixed and PUR plastic wastes and were in the negative range of −0.28 and −1.15 kg CO_2 eq. respectively.

Not many plastic types considered IC without energy recovery as most of the EoL studies in the review made the assumption that the energy is recovered in the form of electricity/and steam when incinerating the plastic wastes. For the EoL option IC with Energy recovery, except for LDPE (negative GWP of −2.86 kg CO_2 eq.), most of the plastic types showed a high GWP in treating 1 kg of different plastics, ranging from 0.76 to 9.16 kg CO_2 eq. despite the assumption that the environmental impacts of generating electricity and steam were credited in most of the studies. This GWP value of 9.16 kg CO_2 eq. for the IC of PET played a significant part in the calculation of CF, where the countries with a higher share of PET in their plastic composition and a high IC share in their plastic waste management resulted in a higher CF (Italy for example).

For the EoL option LA with energy recovery, even though LCIA results for many plastic types were not available, GWP values for the mixed plastics and PET were 0.35 and 11.93 respectively. However, this EoL option was seldom considered in the LCA studies due to the assumption that the conventional plastics do not release any emissions when landfilled, unlike organic wastes and no energy can be recovered from it. In the case of LA without energy recovery, the GWP values were in the range of 0.07 to 1.95 kg CO_2 eq.

The GWP of LA without energy recovery for all the plastic types were lesser than the ones with IC with energy recovery as there is neither a methodology nor a scientific consensus to quantify the environmental impacts and the loss of resources when plastics are landfilled. It was always assumed in the LCA studies that the plastics once landfilled will stay inert and they would not degrade within the time horizon of 100 years, which is the time horizon in which GWP impacts were calculated. Inability to quantify the plastic wastes that are landfilled/dumped is one of the major limitations in the LCA methodology and also plays an influential part in the calculation of CF, wherein if the country disposes or dumps most or all of their plastic wastes in LAs, the impacts, and the CF are still lower than the countries that recover most of their plastic wastes in the form of recycling and IC.

For the other impact indicators, results were available only for the plastic types PE, PET, PUR, and mixed plastics wastes. Therefore, they were not considered for the calculation of the CF. However, the LCIA results of these plastic types are shown in Figures S2–S6, Supporting Information. The GWP of treating 1 kg of different plastic wastes by different EoL options for cut-off approach is shown in Figure 6.

As mentioned earlier, the cut-off approach refers to the accounting of impacts directly caused by the system without taking any credits for reusing the recovered products. Therefore, the environmental impacts calculated using the cut-off approach are the impacts caused directly by the respective EoL options, that is, environmental impacts from the resources consumed during the collection, transportation, sorting, and recycling of the plastic wastes in an MR processes. From Figure 6, it can be found that all GWP values of the plastic wastes across the EoL options are positive and no credits were assigned to the system to make their GWP values negative. In the case of MR, the GWP ranges from 0.03 to 0.92 kg CO_2 -eq. per kg of plastic waste.

For CR, the GWP values were similar to that of their GWP values with avoided burden approach, which could be owing to the fact that the impacts outweighed the credits that might have been accounted for in the avoided burden approach. The GWP of IC without energy recovery for all plastic types is higher than all of the EoL options except for PP which had a GWP of 0.64 kg CO_2-eq. In the case of other impact indicators, plastic types PET, PE, and MP contributes to the majority of the impact. The results of

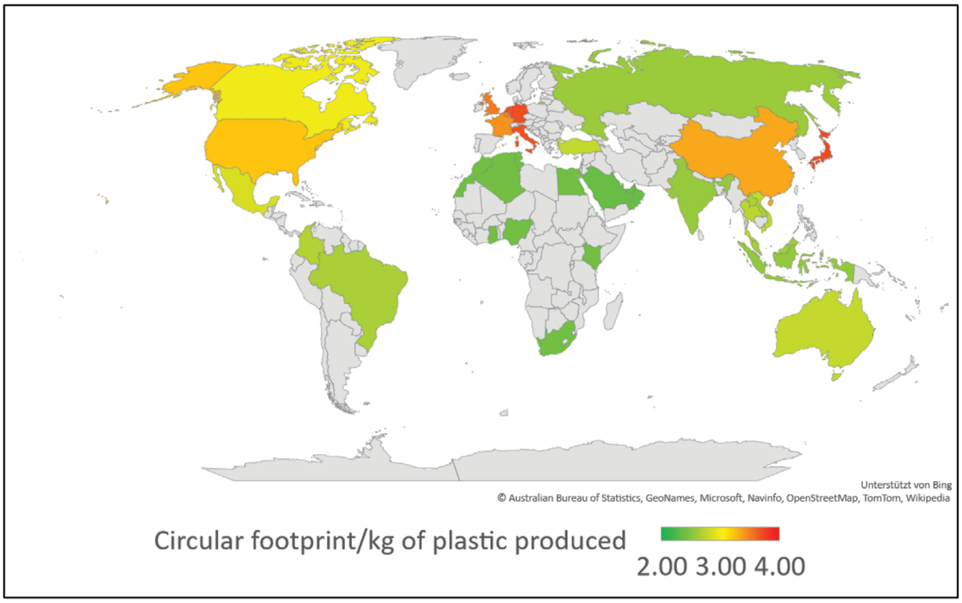

Figure 7. Heat map of CF of different countries per kg of plastic produced (kg CO_2 eq. kg^{-1} of plastic produced).

other impact indicators are shown in Figures S7–S11, Supporting Information.

For the calculation of preliminary CF for selected countries, only GWP values were used in the study due to the unavailability of other impact indicators for all of the plastic types considered in the literature review. The GWP values of the MR by avoided-burden and cut-off approach along with the IC with energy recovery (avoided-burden) and LA without energy recovery (avoided-burden) were used for the calculation of the CF. One of the main limitations of using these results for the calculation of CF was that most of the LCIA results were calculated in these LCA studies with the help of secondary data (literature, generic LCA databases) and therefore will not reflect the reality of the environmental performance of the plastic waste treatments across the world even though the LCA studies were performed in different regions. This is another aspect that has to be considered when identifying the DfR strategies for the plastic products and also justifies the case of local recycling which would definitely increase the quality of data thereby integrating them in calculating the environmental impacts of the recovery processes. Apart from the results, the choice of modeling approach (cut-off or avoided burden or any other approach) is also important when comparing the results of two different product systems. The GWP results of the recycling, IC, and LA processes with avoided burden and cut-off approach are shown in Figures S12–S14, Supporting Information.

3.3. Preliminary Circular Footprint of Plastic Wastes of Different Countries

Using the literature review and average environmental impacts of the EoL options of different plastics, the CF of treating/disposing of the plastic wastes across different countries was calculated. The countries/regions were selected based on two different aspects: 1) Export and import of plastic wastes and plastic scrap in the world[111] and 2) Countries that have a high share of plastics production or dispose most of the used plastic products. By taking the annual plastic production data from different countries as their respective functional units with the respective share of plastic types (only major plastic types like LDPE, HDPE, PP, PET, and PS were considered and the rest were grouped into “Other plastics”) and the GWP values of the virgin plastic resins (obtained from the literature), the GWP of the primary production per functional unit was calculated.

Based on the calculated average impacts of recycling, IC, and disposal from the review along with the individual share of recovery and disposal of plastic wastes in each country, the GWP of the recycling, IC, and landfilling of the total plastic wastes in each country per year was calculated. All of the above parameters along with the quality ratios were used in the CFF to calculate the total environmental impacts of treating the plastic wastes in the respective countries. As the CFs of the countries are associated with the respective functional units (shown in Figure 8 and Table S9, Supporting Information), which is the annual production/consumption/generation of plastic materials, in order to compare between the countries, the CFs were then converted to 1 kg of plastic produced and are then presented in the form of the heat map in **Figure 7**.

The heat map shows the CF of different countries per kg of plastic produced/treated in the respective countries which was calculated based on the composition of the plastic demand and the ways in which the plastic wastes are treated in different countries. The heat map was done with the help of an add-in in Microsoft Excel, where the CF values per kg of plastic produced/treated were entered for respective countries and were then visualized in a world map with different color schemes as shown in Figure 7.

From Figure 7, it can be seen that countries in the Global North like Germany, France, Italy, Netherlands United Kingdom, USA along with the countries like China and Japan have a higher CF per kg of plastic produced/treated (3.34–3.72 kg CO_2-eq. for China and Netherlands respectively) in comparison to the other countries in Asia, Africa and Latin America (ranging from 2.36 to 2.99 kg CO_2-eq.). This higher CF for these countries can be attributed to different reasons like:

- The share of "Other plastics" (All the plastic types apart from HDPE, LDPE, PP, PET, and PS) is higher in these countries (nearly 25 to 56%) compared to the countries in Africa, South America, and Asia (except China and Japan). As the GWP for the primary production, recycling, IC, and landfilling of these other plastics were assumed to be the average GWP of all the virgin plastic types considered in the review along with the impacts of recycling, IC, and LA, the corresponding GWP values were higher in comparison to the GWP of the main plastic types (the GWP values used for the "Other plastics" are shown in Table S8, Supporting Information)
- CF quantifies the environmental impacts of recycling and IC with energy recovery, but due to the lack of standardized methodology (as explained in Section 3.1) in quantifying the loss of resources due to landfilling/open dumping the plastic wastes, the countries that usually recycle and incinerate their plastic wastes have a higher CF in comparison to those countries which have a very low percentage of recycling and IC but dispose (open dumping/LA) most of their plastic wastes. This is one of the major limitations in applying CF to understand the environmental impacts of the plastic waste in different countries
- The data quality and the availability of data on plastic consumption, plastic share, and their disposal in many countries were not consistent and transparent. There have been many discrepancies between the values that are presented in the reports from plastic associations of the respective countries and the reports published by the independent organizations on the plastic consumption and recovery of the same. Therefore, more transparency and completeness in the data will result in a higher CF for those countries with a higher rate of disposal
- In the case of countries in the middle east, southeast Asia, Latin America, and Africa, limited information was available regarding the recycling and disposal of other plastic types. In addition, the recycling quote in these countries was mostly attributed to the informal recycling and therefore the market situation and quality ratios of the recyclates to the input virgin plastic materials might be lower than what was assumed for the calculation of CF (the quality ratios were assumed to be same for the plastics all over the world)

All these aspects play an important and significant role in the resulting lower CF for the countries in the Global South. Another limitation in the calculation of CF in this study was the inability to account for the impacts of plastic wastes exported to other countries which might be downcycled or disposed even though the producer of plastic waste might have a better recycling infrastructure in their own countries.

For example, Australia which recycles only 13% of their plastics has a CF of 2.78 kg CO_2-eq. kg^{-1} of plastic produced/treated in comparison to EU-27 (refers to the European region) which has a CF of 3.43 kg CO_2-eq. kg^{-1} of plastic although EU-27 recycles nearly 33% of their plastic wastes. The difference in the CF lies in the fact that Australia incinerates only 2% of their plastic wastes, whereas the EU-27 incinerates nearly 43% of their plastic wastes, which translates to the accounting of the environmental impacts of the IC of these plastics. Moreover, the environmental impacts of disposing the plastic wastes to LAs, due to the inability of quantifying them in LCA, result in a lower environmental impact irrespective of how much of waste getting disposed of (Australia disposing nearly 84% of their plastic wastes to LAs which also includes exporting some of them to other Asian countries in comparison to the EU-27, which LAs only 25% of their total plastic wastes). Also, a material flow analysis of plastics between countries along with the LCA results of treating every type of major plastics (plastics like PVC, ABS, PC, PA) after use should be performed to develop a comprehensive overview of the flow of plastics all over the world.

Due to the challenges of comparing the CF of different countries per kg of plastic produced/treated, the absolute values of the CF for countries per functional unit are shown in **Figures 8–11** and Table S9, Supporting Information. The absolute values of the CF for different countries were not calculated per kg (unlike the results shown in the heat map). The functional unit here refers to the annual production/consumption/treatment of plastics (depending on whichever data was available) expressed in Million tons and they are country-specific.

The difference between the GWP of the virgin plastic mixtures and the calculated preliminary CF (per annual plastic consumption) for different countries that were considered for this study can be better understood by classifying them into four different geographical regions. They are:

- Europe (including Turkey and Russia)
- Asia and Oceania (middle eastern countries, India, Asian and southeast Asian countries)
- Americas (North + South America)
- Africa

Due to the unavailability of information on the disposal and recovery of plastic wastes in most of the countries across the world, only a few countries were considered for this study. In Figure 8, it can be seen that there is more than a 45% increase in the GWP of disposing the plastic wastes (calculated as preliminary CF) in comparison to the average GWP of the virgin plastic mixture in different countries in Europe. In the case of Turkey and Russia, there is just a 14% increase in the environmental impact (percentage difference between the GWP of the virgin plastic mixture and the calculated preliminary CF) due to the limitation in LCA and CCF in quantifying the environmental impacts of disposing plastic wastes in LAs and both these countries dispose as much as 95% of their total plastic wastes to LAs.

From Figure 9, it can be seen that China, being the largest producer/consumer of plastics in Asia has the largest GWP for their virgin plastic mixture and the corresponding preliminary CF. It can also be found that countries like Thailand, India, and Saudi Arabia, which produce more plastics than the countries in Europe have a higher GWP of their virgin plastic mixture and subsequently their CF in comparison to other countries in the middle east and southeast Asia. But the percentage increase in the environmental impact in these countries is in the range of 17% due

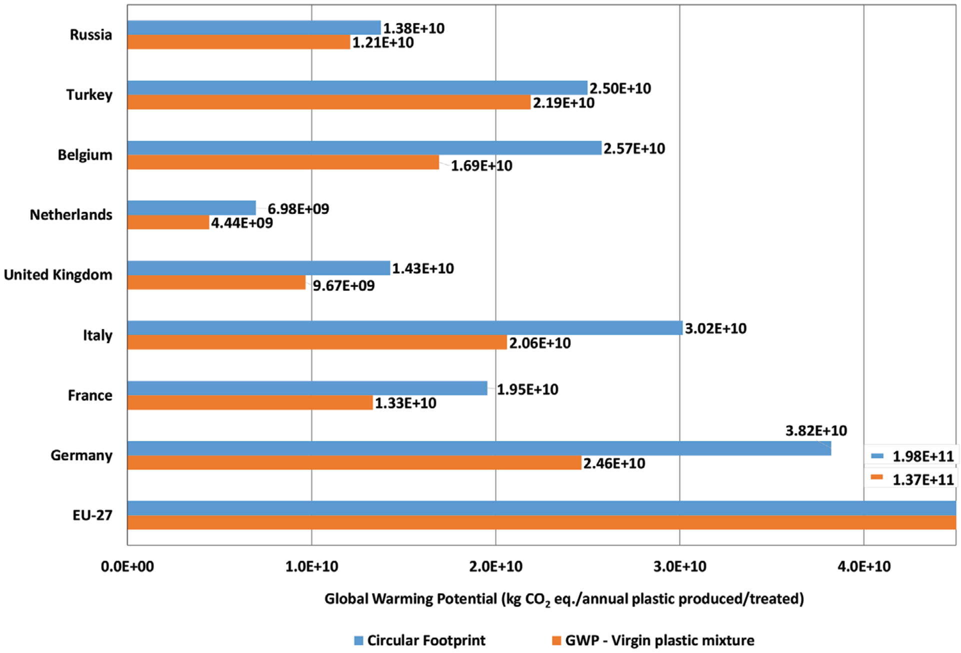

Figure 8. Comparison of GWP between virgin plastic mixture and preliminary CF in Europe + Turkey + Russia.

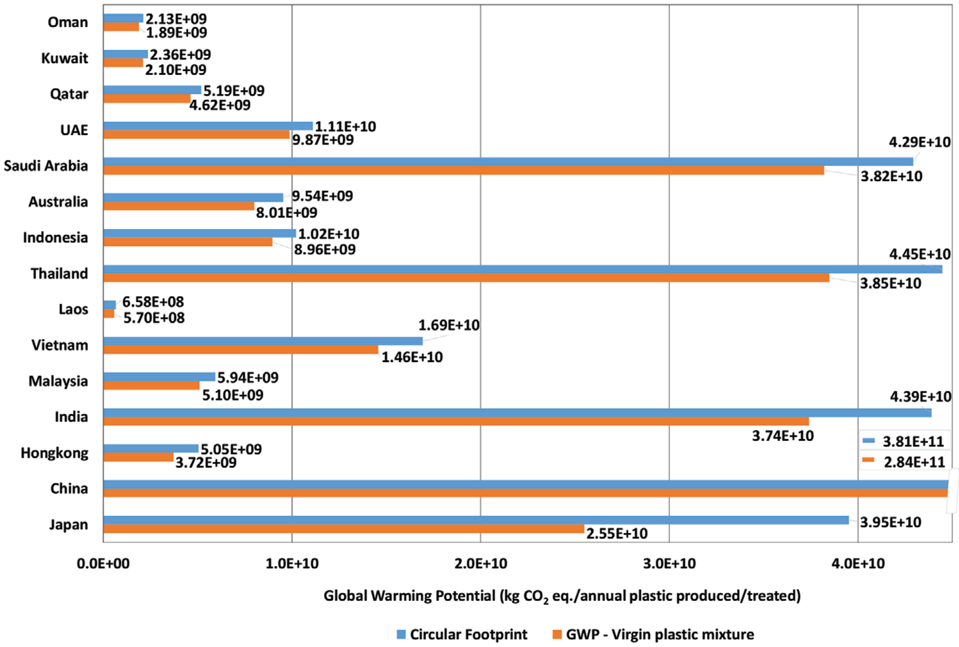

Figure 9. Comparison of GWP between virgin plastic mixture and preliminary CF in Asia and Oceania.

to their lesser share in the production of “Other plastics”, lower recycling quote, and an increased share of disposing the plastic wastes to LA.

In the region Americas, which includes countries from North and South America as shown in Figure 10, USA has the highest GWP of the virgin plastic mixture and the corresponding CF for treating their plastic wastes. The USA produces the largest share of “other plastics” in the Americas, which also contributes to the high environmental impacts. The CF of Mexico and Brazil are comparable due to the similar plastic production capacities. However, Brazil despite producing nearly 8.3 Million tons of plastic every year, recycles a meager 2% of the total plastic waste. Landfilling the rest of the plastic wastes is a cause of concern, especially for the ecosystems.

In the case of countries in Africa, as shown in Figure 11, not much information was available either on the LCA studies on different EoL options or on the production/consumption/disposal of plastics. From Figure 11, it can be seen that countries like

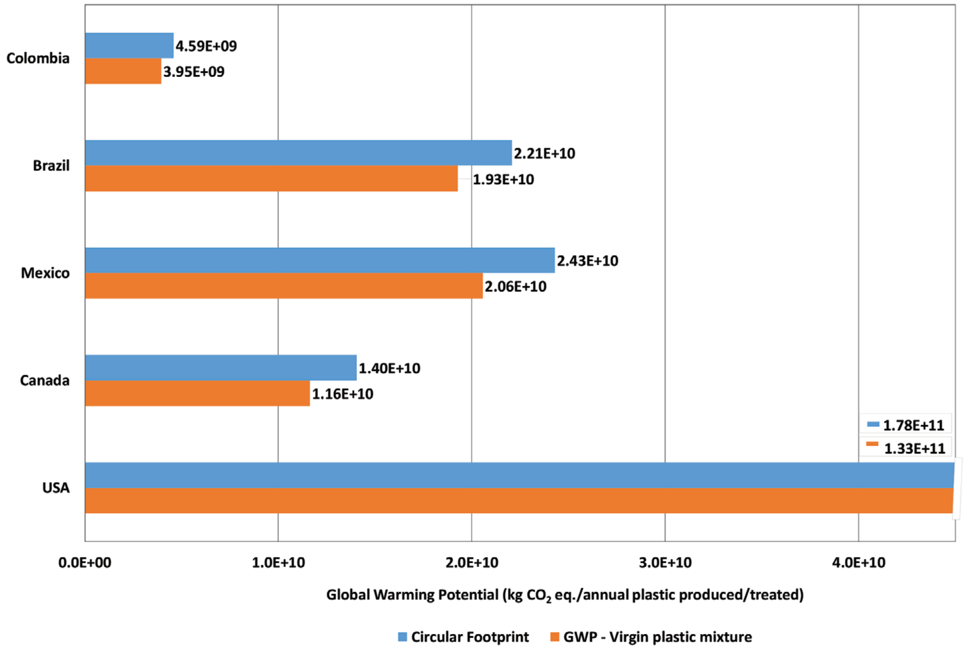

Figure 10. Comparison of GWP between virgin plastic mixture and preliminary CF in Americas.

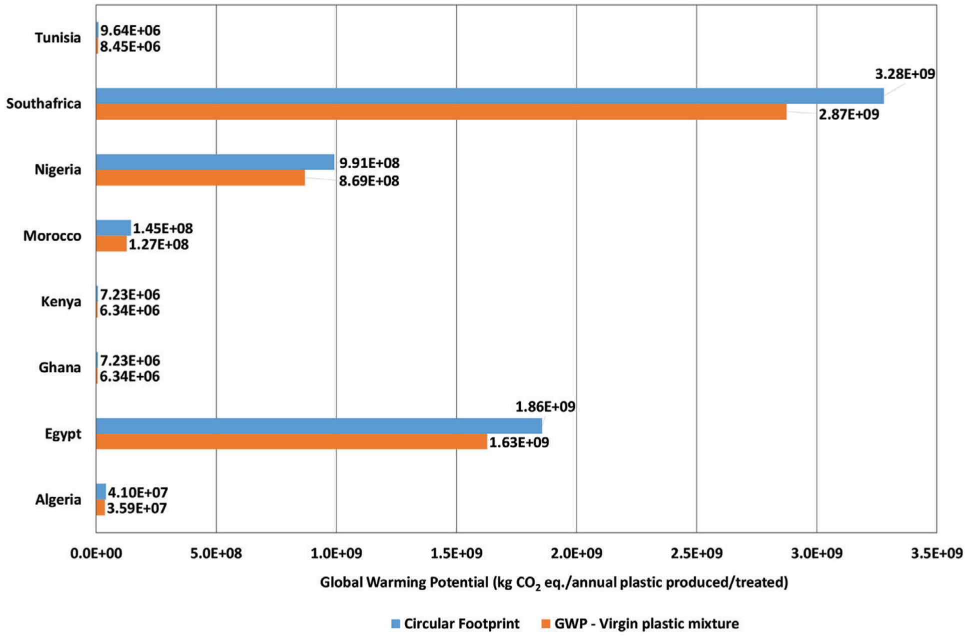

Figure 11. Comparison of GWP between virgin plastic mixture and preliminary CF in Africa.

Egypt, Nigeria, and South Africa contribute to the majority of the plastic production in the continent and apart from the domestic consumption, these countries also export the produced plastics to different countries in the world.

From Figures 8–11 and Table S9, Supporting Information, it can be seen that there is atleast a 14% increase in the environmental impacts (i.e., CF) of the plastic product system in comparison to the environmental impacts of the virgin plastic mixture across different countries. This is because the CF not only includes the environmental impacts of the virgin plastics, but also environmental credits/burdens due to the recycling, loss of quality of the recycled materials (quality ratio), IC, and disposal, which will be higher in comparison to the environmental impacts of the virgin plastic mixture per functional unit.

In the case of European countries, Japan and China there is an increase of 34–57% in the total environmental impacts in comparison to the environmental impacts of the virgin plastic mixture in the respective countries. Also, the CF of

USA (1.78E+11 kg CO_2-eq./annual plastic production), China (3.81E+11 kg CO_2-eq.), and EU-27 (1.98E+11 kg CO_2-eq.) are higher compared to other regions of the world due to their higher annual consumption of plastics, production of different plastic types (higher share of "other plastics") and generation of plastic wastes.

From the absolute values of the preliminary CF per annual plastic production of different countries, it can be observed that the consumption of plastics in the Global South is quite low compared to the Global North. But the mismanagement of the plastic wastes due to the lack of awareness, inadequate infrastructure to treat the wastes, and lack of stringent policy and regulatory frameworks to stop the import of plastic wastes from the Global North, affect the potential of plastics to have a transition from a linear to a circular economy. Therefore, these aspects and the complexities in the value chain of plastics have to be taken into account while identifying the DfR strategies.

Despite the methodological challenges in the calculation of a preliminary CF for plastic wastes for different countries using CFF, especially when it comes to the disposal of plastic wastes, CF is a good starting point to quantify the environmental performance of the plastics beyond cradle to gate, that is, beyond the raw material acquisition and production of the plastics. It does so by accounting for not only the environmental impacts of the production of virgin plastics but also the credits/burdens of the recovery (recycling and IC) and disposal process of the plastic wastes along with the market value and quality of the recyclates, when used in another product system. From the CF, change in the environmental impacts of the plastic product due to its recyclability and quality of the recovered products, could be better understood. This, in turn, will help the manufacturers and countries to identify the DfR strategies during the design phase thereby increasing the recyclability of these plastic products after use.

3.4. Design for Recycling Strategies Based on the Environmental Impacts

Apart from the environmental impacts, there are many aspects that influence the decision-making in designing products and plastics are no exception. With the increase in the consumption of plastics all over the world and the mounting pressure on countries to reduce the same have placed the design of plastic products in an important yet difficult position. To increase the circularity of plastics and to keep the resources as much as possible in use, it is important to not only measure the impacts of the products but to also understand the use and design of the plastic products even before the products were manufactured. Therefore, based on the literature review on the LCA studies, design strategies, and status quo of recycling/disposal of plastics all over the world, DfR strategies were developed in this study. These strategies are divided into four different levels across the value chain of the plastic product system and individual strategies in each level were identified and shown in **Figure 12**.

The levels were defined considering all the life cycle phases of a plastic product system. The decision making and the development of new concepts to increase the recyclability of the plastic products during the design phase must identify strategies at all levels equally and at the same time should not be done sequentially, that is, before the production of the plastic products, emphasis should be made not only on the material selection but also on the availability of sufficient infrastructure to recycle these materials after use. The levels and the associated strategies are explained further in this section.

3.4.1. Material Level

For a comprehensive material selection framework and to improve the recyclability of the products after use, it is important to consider the industrial sector (Automotive, Construction, Packaging) where the plastic product will be used. Once the sector is identified, it is easier to identify their market share and availability of recycling infrastructure to recycle the products. Apart from the application, the functionality of these materials should also be taken into account which involves the analysis of the technical and environmental properties of the materials.

3.4.2. Process Level

On the process level, it is important to identify the choice of process, their environmental impacts, resource efficiency (reuse of the pre-consumer wastes, chemicals), use of additives, use of renewable energy, product composition (monomaterials or a combination of different polymers/metals) and most importantly the ease of disassembly of different components of the product after use. From the literature review, it was found that the recovery of plastics from municipal solid wastes becomes difficult if their components are difficult to disassemble.

3.4.3. Product Level

After identifying the DfR strategies on the material and process level, the processing, distribution, and use of the products should be studied in the design phase. The aspects that have to be considered are extended service life of the products (product as a service, take back schemes, reparability, and availability of spare parts), understanding the logistics and the stakeholders/supplier involved in the distribution and use of products to track the place where the products are being used and communication about the product to the customers and distributors (instruction manual, information on the repair of the products and information on how the products can be safely sent to the collection center after use where they can be reused or recycled)

3.4.4. Waste Level

After the use of plastic products by the customers, they are most likely to end up as waste, which should ideally be collected, sorted, and recycled for further use. However, due to the differences in the collection, sorting, and infrastructure within the same country and across different countries, care must be taken in tracking where the products are usually used and the fate of these products after use must be identified as early as design phase. Even in an ideal scenario, not all the components can be

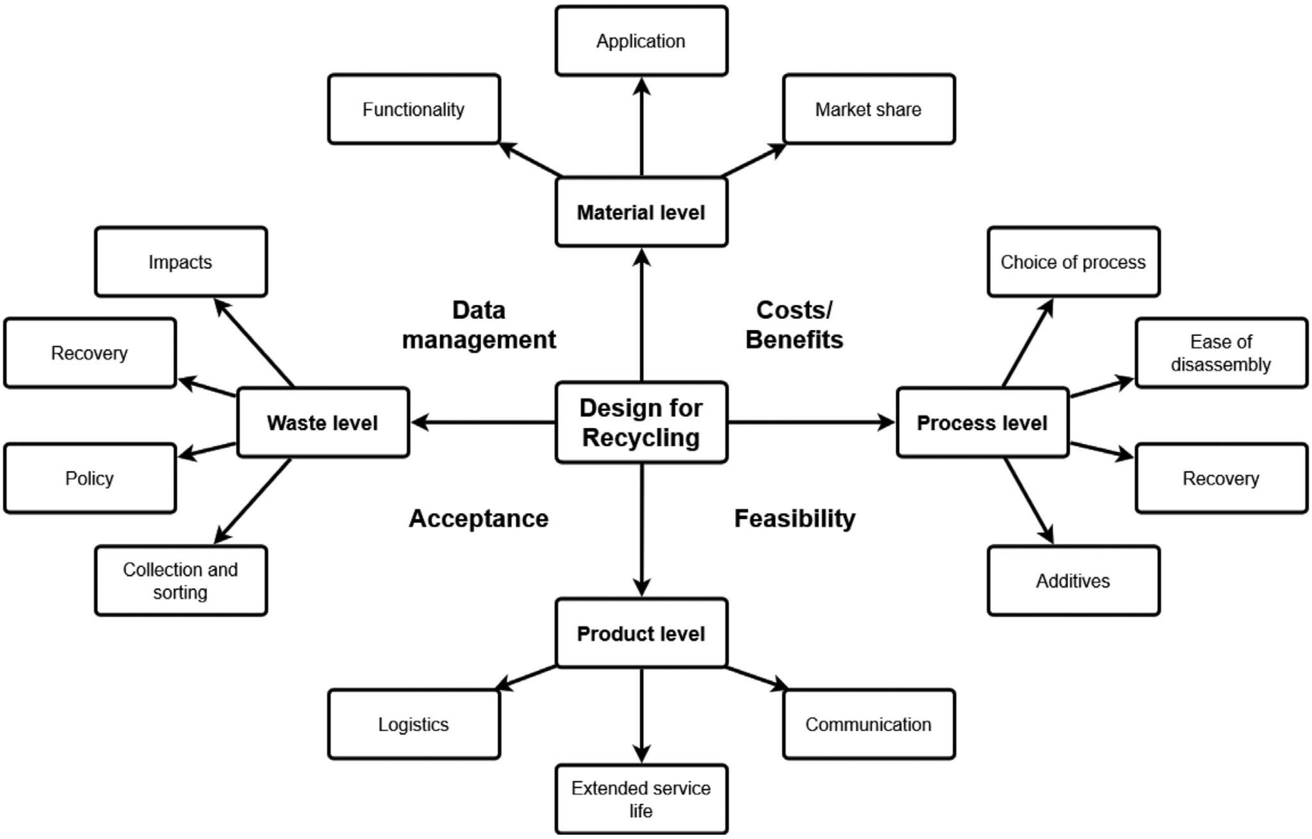

Figure 12. DfR strategies for plastic products.

completely collected and reused for the next cycle. However, care must be taken to recover as many resources as possible. To increase the resource recovery at the end of the life cycle, it is important to consider the infrastructure and policy frameworks of different regions and countries, where plastic products are being used. Apart from this, measures like investing in the recycling infrastructure, ease of sorting and collection can be supported by the industries, and recycling associations so as to include as many resources as possible once again in the value chain.

Apart from these different levels, aspects like costs and benefits for implementing the DfR strategy, feasibility of implementing the process, product, or policy development, a proper data management to collect the data in order to quantify the environmental impacts of the product system and most importantly acceptance among all the stakeholders of the value chain must be considered across the different levels of the plastic product system.

4. Sustainability of End of Life Options: Beyond LCA

Even though LCA is a standardized tool to assess environmental impacts of the product system, for a general estimation about the sustainability of the EoL options, it is also important to look beyond environmental impacts. In fact, such an estimation is only possible if the economic and social performances of EoL options are analyzed as well. Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) are methods developed to display such economic and social performances and to guide decision-makers in order to reduce the impacts and increase positive contributions to sustainable development.[8,9]

In recent years, researchers have tried to combine all three methods into a so-called Life Cycle Sustainability Assessments (LCSA) to enable a more realistic overview of impacts. However, the combination of approaches lacks methodological firmness, which is greatly influenced by the unsound status quo of S-LCA. As Pollok et al. summarize, S-LCA is the youngest of the three methods and lacks standardization despite guiding documents like the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) guidelines for S-LCA of products[112,113] and their methodological sheets or the Handbook for Product Social Impact Assessments (PSIA).[114,115] As a result, existing S-LCA studies are highly individualized and contain various different methodological components. As a result, no uniform and transparent approach exist and studies are rarely comparable.[112,116,117]

Nevertheless, further development and standardization of S-LCA and its application to EoL options for plastic waste would provide valuable insights into the sustainability of such waste treatments. Especially the comparison of LCA and S-LCA results allows depicting which EoL option contributes the most to sustainable development or even contradicts existing political targets like the SDGs. For instance, the previously discussed LCAs have outlined the GWP of MR compared to other EoL options like IC. From an LCA perspective, it is argued that the preferable option is the one that causes the least impact to the environment. From a social perspective, both options could be compared based on the factors like the generation of employment, education, health risks for employees and the society as well as technology development and transfer caused by the physical existence of the waste processing plant.[117,118] In addition, details on employment conditions can change the social performance of EoL options greatly and thus, affects their overall sustainability.

As a result, the most sustainable EoL option would be the one with very little environmental impact while contributing positively to society. Although the results of such a comparison might not always be as straightforward, it would generate greater insights and offer the potential for companies and policymakers to make well-informed decisions and define strategies that are in line with international targets. At the current state, no such comparison exists because EoL options of plastic waste have never been analyzed using S-LCA methodologies before. The further development and testing of S-LCA approaches allow for tackling this research gap and can—if standardized—allow for a holistic Life Cycle Sustainability Assessment covering all the three dimensions of sustainability.

5. Conclusion

Even if a plastic product has been manufactured with low environmental impacts and high resource efficiency, the environmental impacts caused by the use and disposal of these plastic products are not the same across the world. The communication on the environmental performance of the plastic products ends with the factory gate for many product manufacturers citing the lack of data on the use and disposal of their products. To address this problem and to quantify the environmental impacts of recovery and disposal of plastic wastes, a comprehensive literature review on the LCA studies of different EoL options was performed. Subsequently using the environmental impacts analyzed from the study, a preliminary CF was calculated for selected countries taking into account their plastic production and disposal routes.

Despite some of the methodological challenges, lack of data, and limitations, product designer must still consider their EoL options and corresponding CF while calculating the environmental impacts of their products after use. Moreover, the product designer must also consider the fate of their plastic products when used in other countries, where there is inadequate infrastructure to recover these products after use. From the literature review and CF for different countries, DfR strategies were also proposed across different levels, which can guide the product manufacturers to identify complexities in the value chain and most importantly the environmental impacts of their new products during the EoL phase, when exported/manufactured across the world. DfR strategies, when integrated with the product and process development along with the different aspects of sustainability assessment like LCA, Life Cycle Costing, and Social LCA will definitely support the plastic industry transitioning from a linear to a circular economy.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The authors would like to thank the editor team of this special issue for the ongoing support and the review team for their critical feedback and support.

Open access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

circular economy, end-of-life, life cycle assessment, plastics, recycling

Received: February 7, 2022
Revised: March 16, 2022

[1] R. Geyer, J. R. Jambeck, K. L. Law, *Sci. Adv.* **2017**, *3*, e1700782.
[2] J. Völker, F. Ashcroft, Å. Vedøy, L. Zimmermann, M. Wagner, *Environ. Sci. Technol.* **2022**, *56*, 2487.
[3] F. R. Wurm, S. Spierling, H. -J. Endres, L. Barner, S. Spierling, H.-J. Endres, L. Barner, *Macromol. Rapid Commun.* **2020**, *41*, 2000351.
[4] Plastics Europe, Plastics – the Facts 2020, https://plasticseurope.org/knowledge-hub/plastics-the-facts-2020/ (accessed: January 2022).
[5] V. Venkatachalam, S. Spierling, R. Horn, H.-J. Endres, *Proc. CIRP* **2018**, *69*, 579.
[6] S. Spierling, C. Röttger, V. Venkatachalam, M. Mudersbach, C. Herrmann, H.-J. Endres, *Proc. CIRP* **2018**, *69*, 573.
[7] E. Dostatni, J. Diakun, D. Grajewski, R. Wichniarek, A. Karwasz, *Soft Comput.* **2016**, *20*, 4347.
[8] ISO, ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework, https://www.iso.org/standard/37456.html (accessed: December 2021).
[9] ISO, ISO 14044:2006 Environmental management—Life cycle assessment—Requirements and guidelines, https://www.iso.org/standard/38498.html (accessed: December 2021).
[10] C. A. Bernardo, C. L. Simões, L. M. C. Pinto, *AIP Conf. Proc.* **2016**, *1779*, 140001.
[11] Y. Chen, Z. Cui, X. Cui, W. Liu, X. Wang, X. Li, S. Li, *Resour., Conserv. Recycl.* **2019**, *146*, 348.
[12] T. S. Gomes, L. L. Y. Visconte, E. B. A. V. Pacheco, *J. Polym. Environ.* **2019**, *27*, 533.
[13] D. Lazarevic, E. Aoustin, N. Buclet, N. Brandt, *Resour., Conserv. Recycl.* **2010**, *55*, 246.
[14] S. Spierling, V. Venkatachalam, M. Mudersbach, N. Becker, C. Herrmann, H.-J. Endres, *Resources* **2020**, *9*, 90.
[15] T. M. Kousemaker, G. H. Jonker, A. I. Vakis, *Appl. Sci.* **2021**, *11*, 3305.
[16] H. Alhazmi, F. H. Almansour, Z. Aldhafeeri, *Sustainability* **2021**, *13*, 5340.
[17] Plastics Europe, Plastics – the Facts 2021, https://plasticseurope.org/knowledge-hub/plastics-the-facts-2021/ (accessed: January 2022).
[18] J. R. Jambeck, R. Geyer, C. Wilcox, T. R. Siegler, M. Perryman, A. Andrady, R. Narayan, K. L. Law, *Science* **2015**, *347*, 768.
[19] World Economic Forum, The New Plastics Economy: Rethinking the future of plastics, https://www.weforum.org/reports/the-new-plastics-economy-rethinking-the-future-of-plastics (accessed: January 2022).

[20] US, EPA, Plastics: Material-Specific Data, https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data (accessed: January 2022).
[21] J. Pickin, C. Wardle, K. O'Farrell, P. Nyunt, S. Donovan, *Natl. Waste Rep.* **2020**, https://www.awe.gov.au/sites/default/files/env/pages/5a160ae2-d3a9-480e-9344-4eac42ef9001/files/national-waste-report-2020.pdf
[22] D. C. Wilson, C. Velis, C. Cheeseman, *Habitat Int.* **2006**, *30*, 797.
[23] G. research, Global Plastic Waste Management Market Size Report, 2020–2027, https://www.grandviewresearch.com/industry-analysis/plastic-waste-management-market (accessed: January 2022).
[24] A. L. Brooks, S. Wang, J. R. Jambeck, *Sci. Adv.* **2018**, *4*, eaat0131.
[25] H. Johnson, Z. Nay, R. Maguire, L. Barner, A. Payne, M. Taboada, *TEL* **2021**, https://doi.org/10.1017/S2047102521000261
[26] D. Xanthos, T. R. Walker, *Mar. Pollut. Bull.* **2017**, *118*, 17.
[27] World Economic Forum, As Canada bans bags and more, this is what's happening with single-use plastics today, https://www.weforum.org/agenda/2020/10/canada-bans-single-use-plastics/ (accessed: January 2022).
[28] H. L. Chen, T. K. Nath, S. Chong, V. Foo, C. Gibbins, A. M. Lechner, *SN Appl. Sci.* **2021**, *3*.
[29] N. J. Van Eck, L. Waltman, L. Waltman, *Scientometrics* **2010**, *84*, 523.
[30] Elsevier, Scopus – The largest database of peer-reviewed literature, https://www.elsevier.com/en-in/solutions/scopus (accessed: December 2021).
[31] Environment, Circular economy action plan, https://ec.europa.eu/environment/strategy/circular-economy-action-plan_de (accessed: January 2022).
[32] World Economic Forum, Circular Economy, https://www.weforum.org/projects/circular-economy (accessed: January 2022).
[33] Ellen MacArthur Foundation, Plastics and a circular economy, https://ellenmacarthurfoundation.org/topics/plastics/overview (accessed: January 2022).
[34] UNDP, Sustainable Development Goals | United Nations Development Programme, https://www.undp.org/sustainable-development-goals (accessed: January 2022).
[35] D. Moher, A. Liberati, J. Tetzlaff, D. G. Altman, *PLoS Med.* **2009**, *6*, e1000097.
[36] R. Accorsi, A. Cascini, S. Cholette, R. Manzini, C. Mora, *Int. J. Prod. Econ.* **2014**, *152*, 88.
[37] M. Al-Maaded, N. K. Madi, R. Kahraman, A. Hodzic, N. G. Ozerkan, *J. Polym. Environ.* **2012**, *20*, 186.
[38] S. M. Al-Salem, S. Evangelisti, P. Lettieri, S. Evangelisti, P. Lettieri, *Chem. Eng. J.* **2014**, *244*, 391.
[39] H. A. Arafat, K. Jijakli, A. Ahsan, K. Jijakli, A. Ahsan, *J. Cleaner Prod.* **2015**, *105*, 233.
[40] Y. Aryan, P. Yadav, S. R. Samadder, *J. Cleaner Prod.* **2019**, *211*, 1268.
[41] K. M. Bataineh, *Adv. Civ. Eng.* **2020**, *2020*, 8905431.
[42] S. Belboom, A. Léonard, *Biomass Bioenergy* **2016**, *85*, 159.
[43] J. Mendes Campolina, C. São Leandro Sigrist, J. M. Faulstich De Paiva, A. Oliveira Nunes, V. A. Da Silva Moris, *Int. J. Life Cycle Assess.* **2017**, *22*, 1957.
[44] K. Changwichan, S. H. Gheewala, *Sustain. Prod. Consum.* **2020**, *22*, 34.
[45] B. Choi, S. Yoo, S.-I. Park, *Sustainability* **2018**, *10*, 2369.
[46] K. Choudhary, K. S. Sangwan, D. Goyal, *Procedia CIRP* **2019**, *80*, 422.
[47] D. Civancik-Uslu, T. T. Nhu, B. Van Gorp, U. Kresovic, M. Larrain, P. Billen, K. Ragaert, S. De Meester, J. Dewulf, S. Huysveld, *Resour., Conserv. Recycl.* **2021**, *171*, 105633.
[48] C. Clauzade, P. Osset, C. Hugrel, A. Chappert, M. Durande, M. Palluau, *Int. J. Life Cycle Assess.* **2010**, *15*, 883.
[49] A. Demetrious, E. Crossin, *J. Mater. Cycles Waste Manage.* **2019**, *21*, 850.
[50] J. Dong, Y. Chi, D. Zou, C. Fu, Q. Huang, M. Ni, *Waste Manage. Res.* **2014**, *32*, 13.
[51] Franklin Associates, Life Cycle Impacts for postconsumer recycled resins: PET, HDPE, and PP, https://plasticsrecycling.org/images/library/2018-APR-LCI-report.pdf (accessed: January 2022).
[52] J. E. Galve, D. Elduque, C. Pina, C. Javierre, *Int. J. Precis. Eng. Manuf.-Green Technol.* **2021**, *9*, 919.
[53] M. Gear, J. Sadhukhan, R. Thorpe, R. Clift, J. Seville, M. Keast, *J. Cleaner Prod.* **2018**, *180*, 735.
[54] F. Gironi, V. Piemonte, *Environ. Prog. Sustainable Energy* **2011**, *30*, 459.
[55] O. Horodytska, D. Kiritsis, A. Fullana, *J. Cleaner Prod.* **2020**, *268*, 122138.
[56] M.d. U. Hossain, S. T. Ng, Y. Dong, B. Amor, Y. Dong, B. Amor, *Waste Manage.* **2021**, *131*, 412.
[57] T. A. Hottle, M. M. Bilec, A. E. Landis, *Resour., Conserv. Recycl.* **2017**, *122*, 295.
[58] D. Iribarren, J. Dufour, D. P. Serrano, *J. Mater. Cycles Waste Manage.* **2012**, *14*, 301.
[59] H. K. Jeswani, A. Azapagic, A. Azapagic, *Waste Manage.* **2016**, *50*, 346.
[60] H. Jeswani, C. Krüger, M. Russ, M. Horlacher, F. Antony, S. Hann, A. Azapagic, *Sci. Total Environ.* **2021**, *769*, 144483.
[61] M.d.M. H. Khan, V. Laitinen, J. Havukainen, M. Horttanainen, V. Laitinen, J. Havukainen, M. Horttanainen, *Waste Manage.* **2021**, *136*, 93.
[62] H. H. Khoo, R. B. H. Tan, *Int. J. Life Cycle Assess.* **2010**, *15*, 338.
[63] H. H. Khoo, *Resour., Conserv. Recycl.* **2019**, *145*, 67.
[64] Y. Kikuchi, M. Hirao, T. Ookubo, A. Sasaki, *Int. J. Life Cycle Assess.* **2014**, *19*, 120.
[65] Y. S. Lim, T. N. T. Izhar, I. A. Zakarya, S. Y. Yusuf, S. K. Zaaba, M. A. Mohamad, *IOP Conf. Ser.: Earth Environ. Sci.* **2021**, *920*, 012030.
[66] E. J. P. Martin, D. S. B. L. Oliveira, L. S. B. L. Oliveira, B. S. Bezerra, *Waste Manage.* **2021**, *119*, 226.
[67] J. Nakatani, M. Fujii, Y. Moriguchi, M. Hirao, *Int. J. Life Cycle Assess.* **2010**, *15*, 590.
[68] S. Papong, P. Malakul, R. Trungkavashirakun, P. Wenunun, T. Chom-in, M. Nithitanakul, E. Sarobol, *J. Cleaner Prod.* **2014**, *65*, 539.
[69] K. S. Sangwan, V. Bhakar, V. Bhakar, *Procedia CIRP* **2017**, *61*, 738.
[70] J. Santos, A. Pham, P. Stasinopoulos, F. Giustozzi, *Sci. Total Environ.* **2021**, *751*, 141842.
[71] B. Simon, M. B. Amor, R. Földényi, *J. Clean. Prod.* **2016**, *112*, 238.
[72] P. Tratzi, C. Giuliani, M. Torre, L. Tomassetti, R. Petrucci, A. Iannoni, L. Torre, S. Genova, V. Paolini, F. Petracchini, G. Di Carlo, *Recycling* **2021**, *6*, 58.
[73] H. Wang, L. Wang, A. Shahbazi, *J. Cleaner Prod.* **2015**, *87*, 511.
[74] A. U. Zaman, *Int. J. Environ. Sci. Technol.* **2013**, *10*, 1029.
[75] Z. Zhou, Y. Tang, J. Dong, Y. Chi, M. Ni, N. Li, Y. Zhang, *J. Environ. Manage.* **2018**, *227*, 23.
[76] L. Zampori, R. Pant, Suggestions for updating the Product Environmental Footprint (PEF) method, https://eplca.jrc.ec.europa.eu/permalink/PEF_method.pdf (accessed: November 2021).
[77] European Commission, Circular Footprint Formula. Webinar; Environmental Footprint (EF) transition phase, https://ec.europa.eu/environment/eussd/pdf/Webinar%20CFF%20Circular%20Footprint%20Formula_final-shown_8Oct2019.pdf (accessed: November 2021).
[78] D. L. Schrijvers, P. Loubet, B. P. Weidema, *J. Cleaner Prod.* **2021**, *320*, 128800.
[79] T. Ekvall, A. Björklund, G. Sandin, K. Jelse, *Modeling recycling in life cycle assessment*, **2020**.
[80] T. Ekvall, M. Gottfridsson, M. Nellström, J. Nilsson, M. Rydberg, T. Rydberg, *Waste Manage.* **2021**, *136*, 153.

[81] V. Bach, A. Lehmann, M. Görmer, M. Finkbeiner, *Sustainability* **2018**, *10*, 2898.
[82] L. C. Malabi Eberhardt, A. van Stijn, F. Nygaard Rasmussen, M. Birkved, H. Birgisdottir, *Sustainability* **2020**, *12*, 9579.
[83] S. Mirzaie, M. Thuring, K. Allacker, *Int. J. Life Cycle Assess.* **2020**, *25*, 2122.
[84] Y.-C. Huang, J.-C. Tu, K.-P. Kuo, *Adv. Mech. Eng.* **2017**, *9*, 168781401770969.
[85] C. M. V. B. Almeida, A. J. M. Rodrigues, S. H. Bonilla, B. F. Giannetti, *J. Cleaner Prod.* **2010**, *18*, 32.
[86] E. Foschi, S. Zanni, A. Bonoli, *Sustainability* **2020**, *12*, 9738.
[87] F. Alpizar, F. Carlsson, G. Lanza, B. Carney, R. C. Daniels, M. Jaime, T. Ho, Z. Nie, C. Salazar, B. Tibesigwa, S. Wahdera, *Environ. Sci. Pol.* **2020**, *109*, 25.
[88] J. Sherwood, J. H. Clark, T. J. Farmer, L. Herrero-Davila, L. Moity, *Molecules* **2016**, *22*.
[89] B. D. Vogt, K. K. Stokes, S. K. Kumar, *ACS Appl. Polym. Mater.* **2021**, *3*, 4325.
[90] J. Martínez Leal, S. Pompidou, C. Charbuillet, N. Perry, *Sustainability* **2020**, *12*, 9861.
[91] I. Antonopoulos, G. Faraca, D. Tonini, *Waste Manage.* **2021**, *126*, 694.
[92] C. Löw, A. Manhart, S. Prakash, M. Michalscheck, Design-for-recycling (D4R) – State of play, https://www.giz.de/de/downloads/2021-06%20Design%20for%20recycling_barrierefrei.pdf (accessed: February 2021).
[93] L. M. D. Luz, A. C. D. Francisco, C. M. Piekarski, R. Salvador, *J. Cleaner Prod.* **2018**, *193*, 28.
[94] D. Civancik-Uslu, R. Puig, S. Voigt, D. Walter, P. Fullana-i-Palmer, *Resour. Conserv. Recycl.* **2019**, *151*, 104475.
[95] H. Lewis, K. Verghese, L. Fitzpatrick, *Packag. Technol. Sci.* **2010**, *23*, 145.
[96] Á. M. Sampaio, A. M. Sousa, P. Simões, A. J. Pontes, *Polym. Eng. Sci.* **2018**, *58*, 535.
[97] P. Vanegas, J. R. Peeters, D. Cattrysse, P. Tecchio, F. Ardente, F. Mathieux, W. Dewulf, J. R. Duflou, *Resour., Conserv. Recycl.* **2018**, *135*, 323.
[98] A. Navajas, L. Uriarte, L. Gandía, *Sustainability* **2017**, *9*, 1724.
[99] J. Flizikowski, W. Kruszelnicka, M. Macko, *Polymers* **2021**, 13.
[100] A. Berwald, G. Dimitrova, T. Feenstra, J. Onnekink, H. Peters, G. Vyncke, K. Ragaert, *Sustainability* **2021**, *13*, 3923.
[101] E. Du Bois, L. Veelaert, E. Tormans, I. Moons, *Proc. Des. Soc.* **2021**, *1*, 1765.
[102] European Commission, Developer Environmental Footprint, (EF) – Annex C, https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml (accessed: January 2022).
[103] L. Rigamonti, M. Grosso, M. Giugliano, *Waste Manage.* **2009**, *29*, 934.
[104] E. van Eygen, D. Laner, J. Fellner, *Environ. Sci. Technol.* **2018**, *52*, 10934.
[105] A. E. Schwarz, T. N. Ligthart, D. Godoi Bizarro, P. De Wild, B. Vreugdenhil, T. Van Harmelen, D. Godoi Bizarro, P. de Wild, B. Vreugdenhil, T. van Harmelen, *Waste Manage.* **2021**, *121*, 331.
[106] D. Civancik-Uslu, R. Puig, M. Hauschild, P. Fullana-i-Palmer, *Sci. Total Environ.* **2019**, *685*, 621.
[107] J. S. Woods, F. Verones, O. Jolliet, I. Vázquez-Rowe, A.-M. Boulay, F. Verones, O. Jolliet, I. Vázquez-Rowe, A.-M. Boulay, *Ecol. Indic.* **2021**, *129*, 107918.
[108] Leiden University, CML-IA Characterization Factors, https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors (accessed: January 2022).
[109] sphera, GaBi Databases, https://gabi.sphera.com/databases/gabi-databases/ (accessed: January 2022).
[110] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, *Int. J. Life Cycle Assess.* **2016**, *21*, 1218.
[111] K. Buchholz, Which Countries Export & Import Plastic Waste?, https://www.statista.com/chart/18229/biggest-exporters-of-plastic-waste-and-scrap/ (accessed: January 2022).
[112] L. Pollok, S. Spierling, H.-J. Endres, U. Grote, *Sustainability* **2021**, *13*, 10286.
[113] Life Cycle Initiative Guidelines for Social Life Cycle Assessment of Products and Organizations 2020, https://www.lifecycleinitiative.org/wp-content/uploads/2021/01/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-22.1.21sml.pdf (accessed: December 2021).
[114] Life Cycle Initiative Methodological Sheets for subcategories in Social Life Cycle Assessment (S-LCA) 2021, https://www.lifecycleinitiative.org/wp-content/uploads/2021/12/Methodological-Sheets_2021_final.pdf (accessed: December 2021).
[115] Product Social Impact Assessment, Handbook – Product Social Impact Assessment, https://product-social-impact-assessment.com/handbook/ (accessed: January 2022).
[116] M. Kühnen, R. Hahn, *J. Ind. Ecol.* **2017**, *21*, 1547.
[117] B. B. T. do Carmo, M. Margni, P. Baptiste, *Int. J. Life Cycle Assess.* **2017**, *22*, 2007.
[118] Product Social Impact Assessment, Handbook - Product Social Impact Assessment, https://product-social-impact-assessment.com/handbook/#implement (accessed: January 2022).

Venkateshwaran Venkatachalam is a research associate and a Ph.D. candidate at the Institute of Plastics and Circular Economy (IKK), Faculty of Mechanical Engineering, Leibniz University of Hannover, Germany. He received his Master's in environmental and process engineering from the University of Stuttgart, Germany, and has been working in the field of life cycle assessment (LCA) over the past seven years. His research interests are in the integration of sustainability assessment and design for recycling for a circular economy of plastics and composites.

Merlin Pohler was a student researcher at the Leibniz University Hannover (LUH), Germany, and part of the sustainability team of the Institute of Plastics and Circular Economy (IKK). He received his M.Sc. in 2020 from the LUH in Hannover, Germany. His research interests are in the area of circular economy and life cycle assessment with a focus on recycling options and processes for plastics.

Sebastian Spierling is a research associate at the Leibniz University Hannover, Faculty of Mechanical Engineering, and head of the sustainability department of the Institute of Plastics and Circular Economy (IKK). He received a M.Eng. in 2013 from HAWK Göttingen, Germany, and is currently conducting his Ph.D. at the Technische Universität Braunschweig, Germany. His research interest is the area of sustainability assessment (in particular life cycle assessment) in connection with (bio-)plastics, (bio-)composites as well as end-of-life management and circular economy.

Louisa Nickel is a Ph.D. candidate at the Leibniz University Hannover, Institute for Environmental Economics and World Trade (IUW) at the Faculty of Economics and Management and the Institute of Plastics and Circular Economy (IKK). She received her M.A. in sustainability economics and management in 2020 from Carl von Ossietzky University Oldenburg. Her research interest is in the field of sustainability assessment with focus on social life cycle assessments (S-LCA) connected to plastics for automotive applications.

Leonie Barner is the inaugural director of the Centre for a Waste-Free World at the Queensland University of Technology (QUT, Brisbane, Australia). She received her Ph.D. in physical chemistry in 1998 (Georg-August-Universität, Göttingen, Germany). During her career, she has worked in industry, German research institutes (Fraunhofer, Helmholtz), and Australian universities (University of New South Wales, QUT). Besides her research interest in macromolecular synthesis and characterization, she leads a transdisciplinary research center that follows a holistic approach to develop technologies and processes to reduce waste, while using social science knowledge to catalyze change and reduce barriers to participation and adoption.

Hans-Josef Endres is a professor at the Leibniz University Hannover, Faculty of Mechanical Engineering, and director of the Institute of Plastics and Circular Economy (IKK). He received his Ph.D. in mechanical engineering from the Ruhr-University Bochum, Germany, in 1995. During his career, he has worked in industry (BUCK Werke, ThyssenKrupp) and research institutions (Fraunhofer WKI and Hochschule Hannover). His research areas are (bio-)plastics, (bio-)composites, plastic technology, plastic testing, circular economy, and sustainability assessment.