A Survey on Current Practices, Strategies and Research Needs for Circular Manufacturing of Plastics

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Abstract. Advances in manufacturing technology made plastics comparatively inexpensive, light, mouldable and durable. The great success of plastics comes along with a strong negative environmental impact and their accumulation in landfills and leakage into the natural environment is now recognized as a global environmental crisis. The circular economy approach to plastics provides a feasible solution to the prevailing linear system and aims to raise the proportion of plastic that is reused or recycled back into the system. The transition towards a circular economy, cannot be achieved solely through changes within the waste-handling system but must be combined with changes in other parts of the value chain, including the design, the manufacturing, etc. Plastic manufacturing companies need support in the transition. Therefore, this study aims to provide knowledge to plastics companies to move from linear towards circular manufacturing processes. We conduct a systematic literature review examining current practices and research needs in circularity within the plastics industry. This study contributes to the literature by mapping circularity strategies in plastics, explaining innovative circular plastic materials, and highlighting current circular manufacturing technologies such as additive manufacturing and the chemical transformation of waste plastics into various value-added chemical feedstocks, which can replace petrochemicals. Additionally, circular pathways are illustrated to support practitioners in identifying their current position in the value chain and understanding pathways to increase circularity. One of the key conclusions is that circular plastic value chains are still deficient in the implementation of R-strategies (such as rethinking, reducing, reusing, etc.) besides recycling.

Keywords: Circular Manufacturing · Plastics · Literature review

1 Introduction

Advances in manufacturing technology made plastics comparatively inexpensive, light, mouldable and durable [1]. As a result, plastics are a ubiquitous part of modern life and their application area is wide-ranging (e.g., in industrial processes for medicine, high-performance plastics in electronics, etc.). The development of synthetic polymers enables to achieve the desired performance properties of plastics at the lowest cost.

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Thereby, plastics manufacturing processes for commodity polymers use today optimized formulations that include small-molecule additives and co-monomers, combined with tailored polymerization conditions and end-use component production.

However, the great success of plastics comes along with a strong negative environmental impact and their accumulation in landfills and leakage into the natural environment is now recognized as a global environmental crisis [2, 3]. The linear value chain of plastics is one of the primary current sources of CO_2 emissions and environmental pollution. Most of the plastics on a global scale are used only once in industrial processes, products and packaging, etc. and only a small part is reused or recycled [4]. For instance, in Europe, 31% of all plastic waste is sent to landfill, while 39% is incinerated [5]. The linear supply chain is still quite applied in Europe. While the rate of landfilling is decreasing, incineration rates are increasing. The monetary insensitive and strict regulations have not pivoted the plastics industry towards recycling or reuse.

With the increasing awareness of the circular economy, companies are rethinking their business models and using it as a competitive advantage. The circular economy of plastics is a viable alternative to the existing linear system, wherein the plastics are produced, used and disposed of. The purpose of the circular economy is to increase the number of plastics that are reused or recycled back into the system [6]. The transition towards a circular economy, therefore, cannot be achieved solely through changes within the waste-handling system but must be combined with changes in other parts of the value chain, including the design, the manufacturing, etc.

Plastic manufacturing companies need support in the transition. There is a need to investigate the plastics value chain to move from linear to circular. While many studies focus on waste management improving recycling and recovery of plastics waste [7], this study aims to provide knowledge to plastics companies to move linear towards circular manufacturing processes. To achieve the aim of the study, we conduct a systematic literature review (SLR) and examine the following research questions:

1. What are the materials and technologies supporting circular manufacturing of plastics?
2. What are the pathways and stages involved in circular manufacturing of plastics?

2 Method

An SLR was conducted to answer the research questions. The SLR is a review of clearly formulated questions that uses a systematic and evidence-based approach to identifying, selecting, and analyzing secondary data. This approach differs from other review methods because of its transparency, inclusivity, and explanatory and heuristic nature. The main objective of the SLR is to facilitate theory development, align existing research, and uncover areas where additional research is needed [8].

The literature on the circular manufacturing of plastics is fragmented. The SLR is an adequate approach to organizing and unifying knowledge within this field. To be as comprehensive, combinations of generic keyword (and their variants) strings such as “circularity”, “manufacturing, “plastics” are used as search criteria in the Title, Keywords and Abstract. The literature search was primarily carried out on ScienceDirect and Web of Science during the time period of October 2022. Google Scholar was used as a backup to verify that recent articles were not missed. After retrieving the articles from the databases, duplicates were removed, resulting in 498 articles. An essential part of any SLR is establishing inclusion and exclusion criteria to ensure objective reasoning in the choice of literature. Articles from the past decade were included in the review as circular economy is a recent research topic, reducing the original number of 498 articles to 391 after excluding 107. Conference proceedings, professional journals, book chapters, and doctoral dissertations were excluded because significant research would have appeared in refereed academic journals, further reducing the number to 203 after excluding 188 articles. All 203 remaining article titles and abstracts were screened manually and those only vaguely related to circularity, manufacturing, or plastics were excluded, reducing the number to 60 after removing 143 articles. The remaining articles underwent full-text screening to confirm their relevance to circular manufacturing of plastics, resulting in 44 articles after excluding 16. Three highly relevant articles cited multiple times in the 44 articles but not previously identified were added, bringing the total number of articles included in the final review to 47.

3 Material for Circularity

For a material to be considered circular, it must undergo a full life cycle before being reclaimed. The life cycle of plastic products can range from a few days for packaging materials to several years or decades for consumer or industrial products. Plastics are categorized into three groups: elastomers, thermoplastics, and thermosets. The differences stem from the molecular structure of the materials, with thermoplastics being uncrosslinked, while vulcanized rubber and thermosets are crosslinked. The latter is also the main component in composites, and windmill blade cases are discussed in some articles with a focus on the effect of the original product design on the recovery and reuse of composite products [9], and case studies regarding the reuse of materials in additive manufacturing [10]. According to Hildebrandt et al. [11], durable products made of thermosets are more likely to be destined for energy recovery because of the limited recycling options available for this material.

Within the different groups of thermoplastic materials, the are several types of plastics, and only the main types are categorized for recycling. The thermoplastic materials discussed in this study are polyethylene terephthalates (PET), polypropylene (PP), low density (LD) polyethylene (PE), high density (HD) PE, polystyrene (PS), expanded polystyrene (EPS), and acrylonitrile butadiene styrene (ABS), and these are typical volume plastics used in packaging application. Engineering plastics like polyamides (PA), polycarbonate (PC), and polyoxymethylene (POM) are not commonly seen discussed in the reviewed articles. 2 of 47 articles discuss the use of recycling elastomers from end-of-life tire rubber granulate (TRG) in new tires and new products. A study by H. Monteiro et al. [12] shows that recycled TRG has a positive effect on primary energy and carbon emissions, and that supply chain processes, and material production have much higher impacts than the manufacturing of the new products. Bio-plastics and biodegradable plastics are common themes in several articles. Plastic materials from bio-based feedstock can replace fossil-based materials of the same group e.g., PET and PE. These materials can be recycled in the same way. The study by Rybaczewska-Błażejowska et al. [13] shows that recycled PET (rPET) demonstrates the best environmental profile compared to both fossil-based and bio-based PET in all impact categories. Some plastic groups such as polylactic acid (PLA) can only be produced from bio-based feedstocks and are biodegradable under specific conditions.

4 Manufacturing Technologies for Circularity

Advances in technology and processes have increased the circularity of materials. The major current recycling process is dominated by mechanical recycling which sorts and degrades plastics during the process [14]. A large challenge and so barrier is still the quality of the waste material [15]. An empirical study from Swedish manufacturers shows that a high amount of plastics ends up in combustible waste. To reduce this share innovative decontamination technologies for post-consumer waste are needed. The study highlights the importance to reduce the number of varieties of undesired additives used in plastic manufacturing which complicates the sorting process.

An alternative to mechanical is the chemical recycling of plastic waste, and it is seen as a valuable solution enabling the production of feedstock to replace petrochemicals [14]. The chemical recycling process enables the production of higher-quality recycled plastics than mechanical recycling, by depolymerizing polymer chains back to reusable monomers [16]. One of the main challenges is the separation and purification of mixed plastic wastes and multi-component metal-plastic [14]. Mixed fractions of plastics and plastics contaminated with organics are critical in regard to waste management due to the lack of possibilities to be sorted and cleaned to their pure form. Hydrothermal treatment is a prospective solution, which has only been scarcely investigated, but with promising results in processing high-density plastics in order to produce high-value chemical components and recover monomeric constituents [17].

The advances in manufacturing technologies support the circularity of plastics. 12% of the studies introduce additive manufacturing (AM) to reuse plastic waste and produce new products. One example is the use of recycled composite for glass-fiber-reinforced polymers, which is still an open issue regards to end-of-life management [10]. Romani et al. [10] provide promising results regards to tensile test, with the use of mechanically recycled wind blades glass fibers for AM application as an alternative to virgin glass fiber. The degradation of mechanical properties can increase with the number of recycling cycles [18]. 6% of the reviewed studies focus on injection moulding as a prosing path to circular manufacturing. The developments in injection moulding try to maximize the share of recycled plastic materials [19]. A study by Huang et al. [20] shows promising results with the recycling of injection moulded polypropylene material in the sector for renewable energy technologies.

5 Circular Manufacturing Assessment

An effective approach to evaluate circularity strategies in the manufacturing value chain is based on the R-Strategy framework [21]. The findings from the SLR indicate that manufacturing companies are primarily focusing on recycling strategies (as shown in

Fig. 1a, 62.7%). Other R-strategies such as refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, and repurpose are still not widely used, and only a few studies have provided empirical data demonstrating the advantages and decision support in transitioning towards circularity.

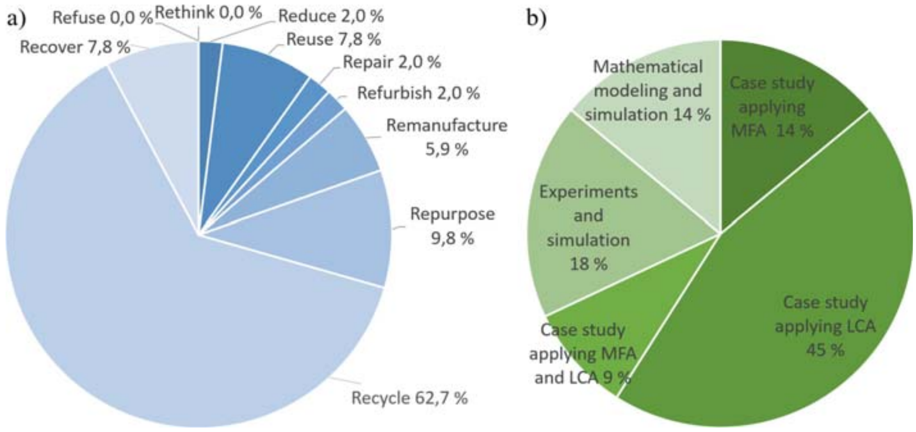

Fig. 1. a) Identified R-strategies, b) Identified circular assessment methods.

Joustra et al. [9] investigate the effect of the original product design on the recovery and reuse of composite products for wind turbine blades as case material. The study highlights the importance and necessity of including circularity aspects in the design phase to enable multiple lifecycles of the composite materials. Moraga et al. [22] examine the use of circular elastomeric materials and analyse different R-strategies (energy recovery, recycling, refurbishing, and reuse) that can reduce the loss of materials and environmental footprint in electronics. The scenarios with cycles of refurbishment and reuse showed improved resource efficiency compared to recycling scenarios. Di et al. [23] highlight the importance and benefits of separating and developing homogenous waste streams. The US has currently still a mixed waste collection system compared to the European countries. European countries have more comprehensive, effective, and separated waste collection systems with up to nine different waste flows that enable to apply of more different R-strategies. The SLR results show that case studies with material flow analysis (MFA) and/or life cycle assessment (LCA), and experiments/mathematical modelling with simulations are the main methods to assess the circularity of products and materials (as shown in Fig. 1b).

Based on the examined research study, we identified the pathways and stages for circular manufacturing of plastics (as shown in Fig. 2). Empirical studies show that advanced manufacturing technologies can effectively utilize recycled materials to produce high-quality products with multiple life cycles. Innovative technologies and methods can also aid in identifying circularity potential in end-of-life and waste management stages, promoting remanufacturing, repurposing, refurbishing, repairing, and reusing strategies. Further, it enables the creation of homogenous waste streams, which enhances the value and quality of secondary materials. By incorporating R-strategies into various stages of the value chain, circularity of products can be increased and material extraction, landfill, and incineration reduced. The framework allows practitioners to determine the extent to which they apply these pathways and their dependency on material extraction and open loop cycles. By analyzing their current practices, practitioners can identify opportunities to improve material efficiency and increase circularity by closing cycles.

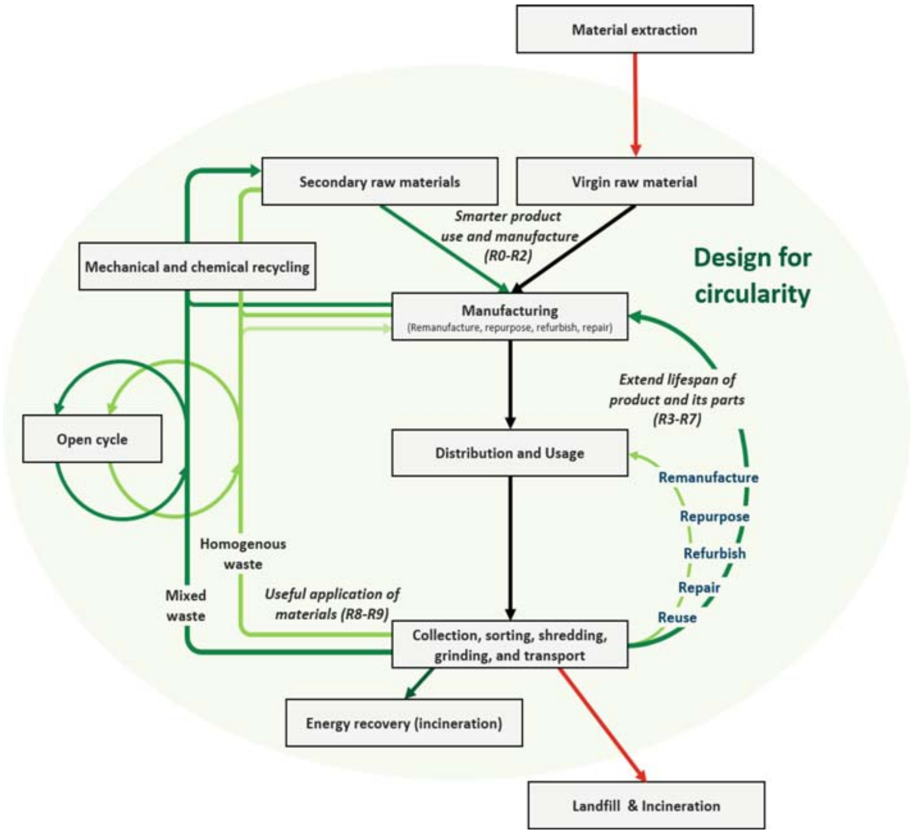

Fig. 2. Pathways and stages in circular manufacturing of plastics.

6 Conclusion

The plastic value chain has primarily focused on improving waste management and recycling processes in recent decades, while other R-strategies aimed at increasing the lifespan of products, parts, and materials have seen limited implementation. Many manufacturers still struggle to transition their value chain from linear to circular. This study confirms, as in several other studies from different industries [24], that some manufacturing companies have started to change their value chain towards circular business models and have seen an improvement in their sustainable performance. These studies have typically focused on specific plastic compositions and niche industries. The lessons learned and technologies applied in empirical studies can enhance the implementation of the circular economy and drive progress towards circular manufacturing. Nevertheless, one of the conclusions of this study is that there is a challenge in generalizing these approaches and applying them to other plastic value chains. The framework presented in this study aims to bridge the gap and assist manufacturers in determining their circularity and their proportion of open/closed loop cycles, and helps determine which value stream partners or networks need to be established or strengthened to close cycles and extend product and material lifecycles.

However, this study has some limitations. The plastic manufacturing industry is comprised of numerous small and diverse companies, and their efforts towards circularity may not be thoroughly documented in research papers. Additionally, there is a possibility of overlooking relevant papers due to the use of keywords and filters. Furthermore, the length constraints of this paper have resulted in only highlighting certain aspects of circular manufacturing in the plastic industry. For instance, the design for circularity in plastics received limited attention. The metrics used in the framework to measure the circularity of different paths could also be refined. Future studies should evaluate the applicability of the introduced framework for manufacturing companies, assess its impact on sustainable performance, and enhance the framework as required.

The SLR aided in identifying future research needs for various pathways. Future studies should develop methods to make plastic products more easily recyclable through the use of mono-material solutions, materials that have an established recycling route and to better measure materials' life cycle performance to increase the life cycles of plastic products. Moreover, a significant challenge for manufacturing technologies such as AM and injection molding is the unpredictable nature of the properties of recycled materials used. Hence, there is a requirement for more research on improved separation methods to guarantee sufficient quality in both mechanical and chemical recycling. Finally, companies require assistance in implementing and utilizing R-strategies that go beyond just recycling and recovery. Further studies should aim to offer techniques and recommendations for utilizing R-strategies to gain a competitive edge.

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