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The impact of secondary materials' quality on assessing plastic recycling technologies

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Abstract. Global plastic production reached a new high in 2019. The high use of plastic leads to a high amount of plastic waste. Thereof, only 33% was collected for recycling in Europe. Plastic production depends on crude oil and energy and has high environmental impacts such as greenhouse gas emissions. The recycling of plastic waste can reduce dependency on fossil resources, help reduce environmental impacts, and achieve sustainability goals. Currently, the chemical recycling of plastic is discussed to complement the existing mechanical recycling. Comparing the recycling technologies is needed to identify and establish the most environmentally and economically promising technology for each waste stream. However, the quality of the recovered material has a high impact on assessment results. This study discusses different assessment metrics for recycling technologies concerning the influence of recovered materials' quality by material substitution rates and circularity potential. In a case study, mechanical and chemical recycling via pyrolysis of HDPE from lightweight packaging waste from Germany is assessed. Mechanical recycling has a lower climate change impact than chemical recycling for material substitution rates above 0.85. On the other hand, chemical recycling has a higher potential to close the plastic loop and retain plastics within the economy due to the higher secondary material quality. The assessment allows evaluating recycling options for the considered plastics from the German collection systems for packaging.

1 Introduction

The amount of plastic produced globally reached a new high in 2019 [1]. The increase in plastic production results in an increasing amount of plastic waste that waste management systems have to handle. In Europe, plastic packaging is the most significant waste fraction, of which 58% is either landfilled or used for energy recovery [1]. Accordingly, there is still great potential for closing the plastic loop. Increased recycling could support achieving sustainability goals within the chemical industry and reduce the dependency on crude oil.

Currently, mechanical recycling is the dominant way of plastic recycling. However, it faces challenges such as non-polymer impurities, polymer cross-contamination, degradation, and additives affecting the material [2]. These challenges negatively impact the quality of the secondary material resulting in downcycling [3]. Therefore, alternative recycling options are

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investigated to complement mechanical recycling. This includes chemical recycling options like depolymerization, gasification, hydrocracking, and pyrolysis that convert plastic waste into feedstocks for the chemical industry to produce potentially primary plastics avoiding downcycling [4].

Mechanical and chemical recycling options have to be compared to identify the most promising technology for each waste stream. The quality of the secondary material impacts comparison. As the material quality of the secondary plastic from mechanical and chemical recycling differs, comparison should include quality assessment. Therefore, this study discusses different assessment metrics for recycling technologies concerning the influence of materials' quality. It focuses on material substitution rates (MSR) within life cycle assessments (LCA) and a circularity potential (CP) defined by Eriksen et al. [5]. Additional performance indicators including the assessment of secondary materials' quality can be found in [6].

2 Material quality in recycling technologies' assessment

LCAs are a methodology to assess different recycling technologies. With the avoided burden approach [7], the MSR comparing primary and secondary materials' quality is included when assessing the environmental impacts of recycling routes [8, 9]. Eriksen et al. [5] introduce the assessment metric CP for recycling technologies to address downcycling, meaning that secondary plastics cannot be used in every application. The MSR (section 2.1) and the CP are described (section 2.2).

2.1 Material substitution rate

Within LCAs, the avoided burden approach rewards the secondary material with burdens associated with a respective primary material production that is avoided using the secondary material instead [7]. The amount of the primary material or the field of application where the primary material can be substituted depends on the secondary material's quality. The quality assessment in MSR captures downcycling of a material compared to the original primary material [10]:

$$LCI_{rec} = (1 - A) * R_2 * (LCI_{recEoL} - LCI_V^* * MSR) \tag{1}$$

$$MSR = \frac{Q_{Sout}}{Q_P} \tag{2}$$

LCI_{rec}: Life cycle inventory of recycling with credits for avoided primary material [-]
A: Factor for allocation of burdens and credits between supplier and user of the material [-]
R_2: Proportion of the material in the product that will be recycled in a subsequent system [-]
LCI_{recEoL}: Specific emissions and consumed resources arising from recycling [-]
LCI^*_V: Specific emissions and consumed resources arising from acquisition and pre-processing of primary material [-]
Q_{Sout}: Quality of the ongoing secondary material at the point of substitution [-]
Q_P: Quality of primary material [-]

Equation (1) calculates the life cycle inventory of a recycling option. The recycling process's emissions and environmental impacts (LCI_{recEoL}) are reduced by environmental impacts arising from primary material production (LCI^*_V). The reduction is determined by the MSR comparing the secondary material's (Q_{Sout}) with the primary material's quality (Q_P)

(see Equation (2)). With an MSR = 1, secondary and primary materials' quality are identical, and the secondary material can replace the primary material in all applications. With an MSR = 0, no primary material can be substituted.

2.2 Circularity potential

The CP assesses the potential of recycling systems to contribute to a specific material's circularity in the long term [5]. It includes the impact of downcycling and highlights applications where the secondary material can be employed. Therefore, physical losses (Equation (3)) and quality losses (Equation (4)) are considered, and the market sizes for secondary material and primary material applications are compared [5]:

$$\eta^{rec} = \frac{M^{rec}}{U^{rec}} \tag{3}$$

$$c^{rec} = \eta^{rec} * \frac{MS(Q^{rec})}{MS(Q^{disp})} \tag{4}$$

η^{rec}: Resource recovery efficiency [-]
M^{rec}: Amount of material recovered [kg]
U^{rec}: Resource potential in the waste stream [kg]
c^{rec}: Circularity potential [-]
MS: Market share where materials with quality level Q or lower can be applied [%]
Q^{rec}: Quality of secondary material [low, medium, high]
Q^{disp}: Quality of potentially displaced primary material [low, medium, high]

The quality of the secondary material (Q^{rec}) is defined by the amount of non-plastic items and non-targeted polymers in the waste stream [5]. Eight key applications for plastic in Europe are identified. They are assigned to three quality groups (low, medium, high) according to acceptable impurity levels based on legislation and quality criteria defined by plastic reprocessing facilities. Low-quality material can be used for building and construction, automotive applications, or other applications with minimal legal restrictions [5]. Medium quality material can be additionally applied in toys, pharmaceutical packaging, and electronics. A high-quality material is also suitable for food packaging [5]. The assigned quality class of the secondary material obtained from a recycling technology and the market share of applications of that quality class determines the CP of the recycling technology.

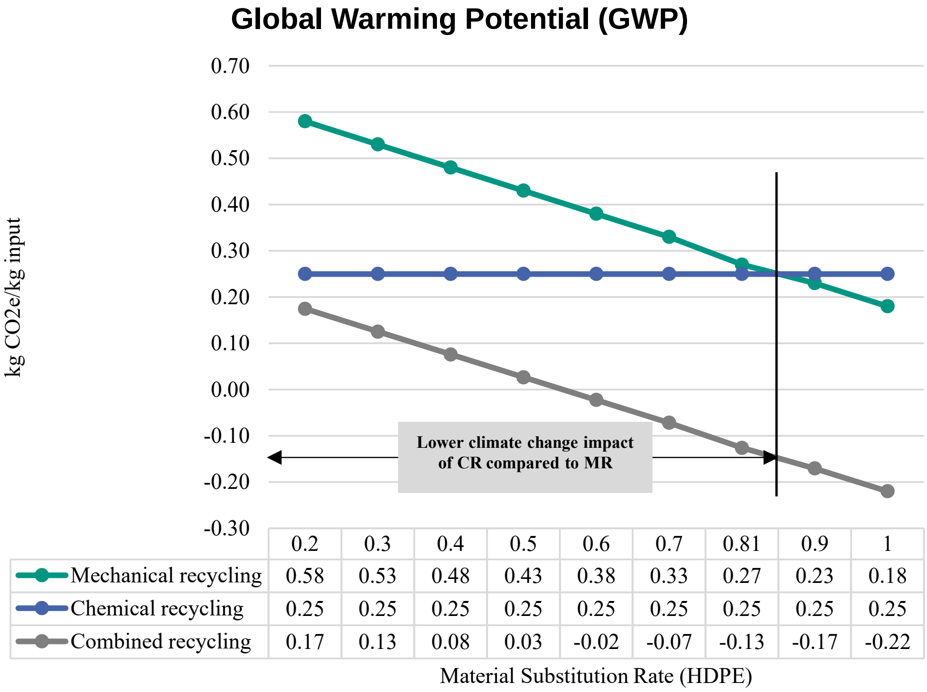
3 Applying assessment methods in a case study

Volk et al. [9] assess three recycling routes for plastics from lightweight packaging (LWP) waste in Germany. They assess a mechanical recycling route producing secondary plastics, a chemical recycling path producing primary-like plastics, and a combination of mechanical and chemical recycling where a share is processed to the secondary plastic and to the primary plastic, respectively. Due to data availability, MSR and CP are discussed based on this case study.

3.1 Material substitution rate

The impact of the MSR on the global warming potential (GWP) assessment results is demonstrated, as it influences the avoided burden for the substitution of primary plastics in mechanical recycling (see Figure 1) [9]. With a lower MSR, the secondary material has a lower quality than the primary material and potentially replaces less initial primary material.

Thus, the reward for associated GWP decreases. This increases the net environmental impact of the mechanical recycling routes. Regarding GWP, the environmentally favoured recycling path changes at an MSR of 0.85, where 1 kg of mechanically recycled secondary plastics substitutes 0.85 kg of primary plastics (Figure 1).



	0.2	0.3	0.4	0.5	0.6	0.7	0.81	0.9	1
Mechanical recycling	0.58	0.53	0.48	0.43	0.38	0.33	0.27	0.23	0.18
Chemical recycling	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Combined recycling	0.17	0.13	0.08	0.03	-0.02	-0.07	-0.13	-0.17	-0.22

Figure 1: Climate change impact of the assessed recycling paths depending on the material substitution rate. Results are displayed for HDPE. Based on [9] (assumptions: $A = 0$, $R_2 = 1$, $L_{recEoI} = const.$).

3.2 Circularity potential

In addition to [9], the CP for the recycling paths is calculated for HDPE (Figure 2). The resource recovery efficiency on the mechanical recycling route is lower ($\eta^{rec} = 0.29$[1]) than on the chemical recycling route ($\eta^{rec} = 0.71$[2]) due to higher material losses. For mechanical recycling, homogenous waste streams are needed, and, e.g., mixed plastics or multi-layer packaging cannot be recycled. It is assumed that HDPE from miscellaneous plastic packaging can be recovered on the chemical recycling route. In the combined approach, the resource recovery efficiency is nearly as high as on the chemical recycling route ($\eta^{rec} = 0.70$[3]) due to the chemical recycling of sorting residues from the mechanical recycling route.

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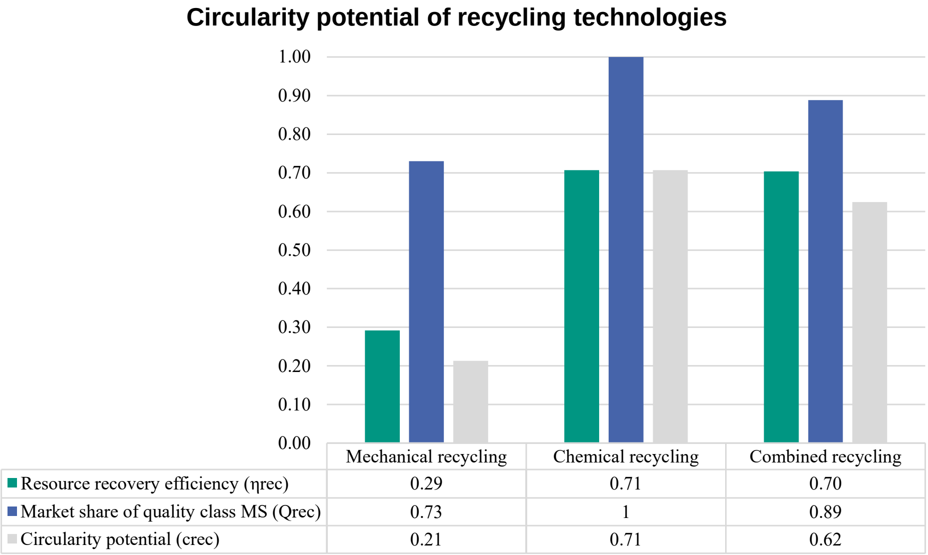
[1] Based on 0.02 kg HDPE after regranulation from 1kg mixed LVP waste input. The total amount of HDPE in the input stream is 0.07 kg.

[2] Based on 0.05 kg HDPE after chemical recycling route via pyrolysis and steam cracking. It is assumed that pyrolysis oil replaces naphtha in steam cracking. The total amount of HDPE in the input stream is 0.07 kg.

[3] High-grade recyclable HDPE is recycled mechanically and miscellaneous plastics are chemically recycled resulting in combined 0.05 kg of the secondary HDPE. The total amount of HDPE in the input stream is 0.07 kg.



	Mechanical recycling	Chemical recycling	Combined recycling
🟩 Resource recovery efficiency (ηrec)	0.29	0.71	0.70
🟦 Market share of quality class MS (Qrec)	0.73	1	0.89
⬜ Circularity potential (crec)	0.21	0.71	0.62

Figure 2: Circularity potential of the assessed recycling technologies for HDPE in [9].

Per definition, the primary plastic is considered to be of high quality [5]. Therefore, the market share for the potentially replaced primary material is 100% ($MS(Q^{disp}) = 1$). The application of the mechanically recycled secondary plastic within food packaging is limited due to required high-quality standards in legislation [11]. Therefore, it is assumed that the mechanically recycled secondary plastic falls within the medium quality class. Based on an overview of the European polymer market [5], the market share of the mechanically recycled secondary plastic (market share of medium or low-quality HDPE) is 73% ($MS(Q^{rec}) = 0.73$). It is assumed that chemically recycled secondary plastics are of high quality and can be applied in all application classes [9]. The market share of chemically recycled secondary plastic is 100% ($MS(Q^{rec}) = 1$). In the combined recycling, 42% of the waste is recycled mechanically, and 58% is recycled chemically. Thus, the weighted market share of the combined approach is 89% ($MS(Q^{rec}) = 0.89$). This results in a CP for the mechanical recycling of HDPE of 21%, assuming a steady-state HDPE market and no material losses. Chemical recycling has a CP of 71%, and the combined recycling approach has a CP of 62%. Besides different recovery efficiencies, the different qualities of mechanically and chemically recycled plastics lead to the different circularity potentials of the recycling technologies.

3.3 Comparing and discussing MSR and CP

MSR and CP are not directly comparable, as the CP does not impact the LCA results but is a separate performance indicator. However, both MSR and CP assess secondary materials' quality facing the challenge that quality is not further defined, and there is no consistent methodology to assess it. The European Commission [12] formulates three approaches to compare material quality based on (1) material analysis and physical indicators, (2) economic indicators, or (3) qualitative discussions. However, they do not establish a uniform definition of a material's quality. A material analysis allows the establishment of its quality based on technical properties, such as molecular weight, tensile strength, or density [13]. A possible economic indicator would be the market price of the secondary material [8], where the differences between the market value of primary and secondary materials are an approximation for material quality differences. Alternatively, a qualitative discussion of the material quality and a sensitivity analysis is possible [9]. Often, the available data dictate the indicator used to compare material qualities.

The methodology of the CP highlights the challenges in quantitatively evaluating material qualities. Secondary materials' quality is assessed by defining three quality classes focusing on non-plastic items and non-targeted polymers in the waste stream [5]. Degradation and the presence of additives [2] are excluded due to few data [5]. Furthermore, a single indicator cannot represent the quality for all possible application types [5] as the quality of plastic depends on a wide range of properties such as physical and chemical composition. Moreover, three quality classes might not capture the wide range of plastic applications.

Regardless of how secondary materials' quality is measured, it impacts the assessment results of environmental indicators and CP. A decrease in materials' quality results in a decreasing performance of the assessed recycling systems. All in all, MSR and CP are not comparable but deal with the same challenges assessing secondary materials' quality.

4 Conclusion

Two approaches were introduced and compared that integrate the quality of the secondary material into recycling options' comparison. The MSR is part of the avoided burden approach within LCAs. The CP is a performance indicator for recycling systems focusing on the potential to close the material loop. Although the approaches are not directly comparable, they face the same challenge of determining and assessing the quality of secondary materials. However, there is no single or standard definition for plastic material quality and, therefore, there are multiple ways to determine it. A standardized approach to assess secondary material quality is lacking to ensure comparability of assessments, and approaches depend significantly on available data. Before utilizing economic indicators, a material analysis should be done, and qualitative discussions can be conducted when no data are available. In general, using a single indicator to represent secondary material quality seems insufficient, as the quality of plastic depends on a wide range of properties. Additionally, multiple metrics should be used to assess plastic recycling technologies. This is highlighted by the inconsistent results for MSR and CP indicating the lowest global warming potential is achieved combining mechanical and chemical recycling, however, outlining that the highest circularity potential provides the chemical recycling of LWP waste.

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