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Perceptions and alignment on quality along the circular plastics packaging material chain

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ABSTRACT

In plastics recycling, quality is increasingly important but not unequivocally determined, as there is a wide range of perceptions on what it actually means. This exploratory research offers insights into how different actors perceive quality in the plastics packaging material processing chain. By conducting semi-structured interviews, we gathered data on quality perceptions from polymer producers, converters, brand owners, waste management companies, mechanical recyclers, chemical recyclers, additive producers, and equipment manufacturers. The results show that, depending on the position of the actors in the chain, their perceptions of the concept quality differ. We categorized the quality criteria they use into nine quality categories: purity, uniformity, mechanical properties, physical properties, processability, functionality, regulations & safety, substitutability and circularity. The interviews revealed specific differences in quality perceptions between the actors in the chain, which can complicate the efficiency of the recycling system. Despite these differences, many quality perceptions do match those of the previous and subsequent actors in the value chain but are not necessarily acknowledged as such.

1. Introduction

Due to the planetary crises, shifting to a circular economy has become a challenging core objective for all industries (Lieder and Rashid, 2016; Mhatre et al., 2021; van Buren et al., 2016). To advance circularity, industries are anticipated to operate within planetary boundaries (Rockström et al., 2009; Steffen et al., 2015). The plastics industry has a significant role in transitioning to a circular economy, with recycling playing a pivotal role in this (Hahladakis and Iacovidou, 2019; Schwarz et al., 2021; Shamsuyeva and Endres, 2021; Lange et al., 2024). This paper focuses on the packaging chain because packaging is currently the largest application for plastics with around 40 % of the total plastics applications (Plastics Europe, 2023) and more than 60 % of the collected post-consumer plastic waste (Plastics Europe, 2022a). Next to increasing recycling rates, achieving high quality in plastics recycling is a central topic of research for the plastics industry (Eriksen et al., 2018; Faraca and Astrup, 2019). Different studies exist on how quality can be improved in different parts of the material chain (Eriksen and Astrup, 2019; Klotz et al., 2022; Roosen et al., 2023; Tratzi et al., 2021). Moreover, literature regularly emphasizes the need for collaboration between actors to improve recycling (Hahladakis and Iacovidou, 2019; Johansen et al., 2022). However, no studies exist on the employed definitions of quality by the actors along this material chain and how these compare.

Existing quality definitions in studies on waste management seem to focus on the composition of the waste stream (Eriksen and Astrup, 2019; Roosen et al., 2022), whereas studies on recycling focus more on material properties, such as mechanical, processing, and physical properties (Boz Noyan et al., 2022; Dahlbo et al., 2018; Tratzi et al., 2021). Recent literature on plastics recycling tends to define quality as substitutability of recyclate for virgin plastics (Eriksen et al., 2018; Klotz et al., 2022; Vadenbo et al., 2017). Several frameworks take a more holistic approach, describing the substitution also based on market and environmental criteria (Caro et al., 2023; Eriksen et al., 2018; Schulte et al.,

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2023; Stallkamp et al., 2022). Tonini et al. (2022) provide a comprehensive overview of quality definitions used in recycling. However, when directly talking to different actors in the chain, they give different meaning to the concept of quality, relevant for their own context. The many different approaches to quality studies and real-life quality discussions with actors indicate a need to understand 'quality' among actors in the material chain. Since literature indicates that quality definitions differ along the chain and can be context-dependent, we use the term 'quality perception' to describe how different actors understand quality.

This exploratory research aims to provide insights into the quality perceptions of actors in the plastics packaging material processing chain (from here on referred to as 'material chain') in Europe. To systemically improve the quality in the chain, it is important to first understand these different perceptions and interactions within this material chain. There is existing research on actors and quality (Iacovidou et al., 2019; Klotz et al., 2022; Picuno et al., 2021; Roosen et al., 2023), however, most studies in the plastic industry focus on one aspect of the material chain and the differences in quality perceptions of actors along the plastic material chain have not been studied. Because of this lack of current literature available on differences in definitions and perceptions of quality across the material chain, this research is still in the nascent phase, which suits a qualitative research approach well (Edmondson and McManus, 2007). We use semi-structured interviews to gain insights into these perceptions of quality and focus on the actors here as the technical stakeholders that play a direct role in the material chain.

2. Quality in literature

Quality throughout the plastics chain is not unequivocally defined. Actors can have different perceptions of value (Velter et al., 2020), which shows that there might be differences in quality perception. The foundation of quality literature was written decades ago (Forker et al., 1996; Garvin, 1984; Reeves and Bednar, 1994; Seawright and Young, 1996), of which Garvin (1984, 1996) describes generic quality categories related to eight dimensions: performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality. Iacovidou et al. (2019) argue that traditional definitions of quality are not accurately representing reality. Instead, they suggest the following definition for quality of materials, components, and products (MCP):'the remaining functionality described via the inherent, designed and created characteristics of a recovered MCP that make it suitable for the same or a different application measured against the properties required for assuring good performance and public safety in the specific application.' Functionality is also highlighted by Tonini et al. (2022), who provide an overview of keywords and terms related to quality of recycling used in literature (such as, impurity content, technical quality, and circularity potential). This more holistic approach to quality has been widely accepted in literature (Caro et al., 2023; Eriksen et al., 2018; Schulte et al., 2023; Stallkamp et al., 2022). One of the terms also discussed by Tonini et al. (2022), substitutability, has been a main quality criterion for plastic recycling in recent literature (Eriksen et al., 2018; Klotz et al., 2022). Several studies provide tools to measure substitutability based on technical properties (Demets et al., 2021; Golkaram et al., 2022; Huysveld et al., 2022; Klotz et al., 2022; Rigamonti et al., 2020).

Empirical recycling studies focus more on material properties, such as mechanical properties, processing properties, and physical properties (Boz Noyan et al., 2022; Dahlbo et al., 2018; Tratzi et al., 2021). In waste management, the step before recycling, studies focus on the composition of the waste stream (Eriksen and Astrup, 2019; Roosen et al., 2022). Quality in plastics recycling is also described as related to regulations & safety aspects (Eriksen et al., 2019, 2018; Faraca and Astrup, 2019). Eriksen et al. (Eriksen et al., 2018), for example, describe plastics for food applications to be of high quality because of its strict application regulations. Products of medium quality to them are toys, pharmaceuticals, and electrical equipment. Low-quality products are then building and construction, non-food packaging, automotive, and others. As such, several perceptions of quality exist, ranging from generic to specific quality categories for quality in specific phases of plastics recycling. In this research, we will create an overview of the relevant quality categories per actor in the plastics material chain.

3. Methodology

3.1. Actors and the material processing chain

The plastics packaging system consists of a complex network of actors, the descriptions of which differ in literature. Some studies describe actors such as producers, converters, consumers, waste managers, and recyclers (Aristi Capetillo et al., 2022; Çevikarslan et al., 2022; Milios et al., 2018), whereas other studies tend to cluster activities in the chain into production, consumption, and waste management (Cimpan et al., 2023; Sanabria Garcia et al., 2023). Moreover, research varies in terms of actors included and excluded. Producer Responsibility Organizations (PROs) are included in some studies (Andreasi Bassi et al., 2020; Çevikarslan et al., 2022; Gerassimidou et al., 2022), as well as organizations such as government or NGOs (Gerassimidou et al., 2022; Grodzińska-Jurczak et al., 2022).

Overall, previous studies encompass a range of actors across a broader value chain, engaging in activities which contribute to or extract value from the system. Our study centers on technical actors in the material chain, because they are at the center of the system, having a direct role in converting input products into output products. Our studied actors include: polymer producers, additive producers, converters, brand owners, waste management companies, mechanical recyclers, and chemical recyclers. We exclude governments and PROs because they do not physically process the materials. We do recognize that consumers and retailers play a significant role in the value chain, but they are outside the scope of this research. Retailers and consumers are excluded because they do not convert an input product into a distinct output product. Moreover, consumers are not an organization, unlike the other actors. Fig. 1 provides an overview of this described material chain.

We emphasize mechanical recycling because it remains dominant (SYSTEMIQ, 2022). We include chemical recycling due to its increasing (expected) utilization as a recycling method (Dogu et al., 2021; Qureshi et al., 2020; Solis and Silveira, 2020). Although numerous techniques exist for chemical recycling (AMI, 2024; Ragaert et al., 2023; Rizos et al., 2023), we mainly consider the pyrolysis process. This emphasis is based on its documented suitability for polyolefins (Kusenberg et al., 2022b; Qureshi et al., 2020), which are extensively used in packaging applications (Palkopoulou et al., 2016; Plastics Europe, 2022b).

Several studies describe how different quality parameters can be measured in polymer production, collection, mechanical recycling, and chemical recycling, and the accompanying efforts required and its complexity (Demets et al., 2021; Genuino et al., 2022; Kasper et al., 2025; Ohshima and Tanigaki, 2000; Velzen et al., 2019). How quality is measured by each actor for their input and output product is out of scope for this research.

Fig. 1 provides a simplified overview of the input and output products of each actor. We define input products and output products as the materials or articles that enter and leave a facility operated by actors (excluding by-products). For instance, the input product for a converter could be plastic pellets and the output product packaging. Additionally, we acknowledge that there is ongoing vertical integration within the material chain, where actors take up other roles in the chain than their original ones (Gao et al., 2023). Contrarily, some actors also partially fulfill the function of another actor. For example, some actors produce polymer film from pellets, which is then supplied to a converter that converts this film into the final packaging. We categorize both as converters in this case.

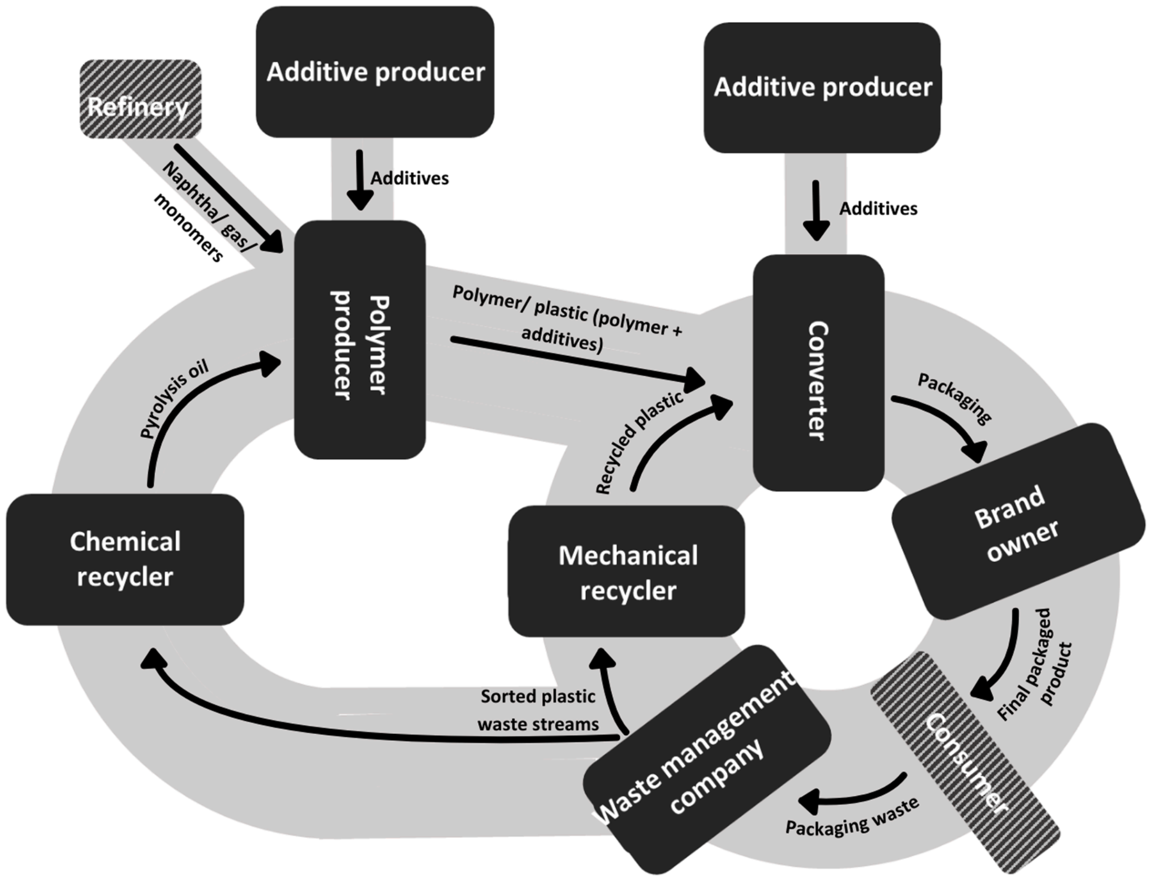

Fig. 1. Overview of actors in the studied material chain. Only the flow of the material in a circular system is visualized, the line thickness does not represent the actual volumes in the material flows and losses are not included in this Figure.

Important to note is the difference between polymers and plastics. Polymers are defined as the pure substance coming out of the polymerization process, whereas plastics are defined as a material or combination of polymers and/ or additives (ISO/TC61/SC1, 2013). Except for the output of the polymer producer, we focus in this paper on plastics since the end product is packaging made from plastics.

As a minority component to plastic packaging, we include additive producers in the system. For these additive producers, we apply a quite broad definition. We include both producers making additives going into the polymer such as stabilizers, antioxidants, and pigments, as well as producers of functional materials, such as inks and adhesives. The former are used as input product at the polymer producers and the latter as input product for the converter.

3.2. Data collection

For data collection, semi-structured interviews were conducted with stakeholders active in Europe. This enabled us to stay on topic while simultaneously also being able to discover novel research areas (Verhoeven, 2016). In total, 28 participants from eight actor groups in the material chain were interviewed, of which fifteen interviews were in Dutch and thirteen in English.

Table 1 provides an overview of the represented actors and their discussed primary input and output products during the interviews. The participants were specifically selected based on their knowledge and experience by using a purposive sampling method (Bell et al., 2019). To anonymize the interviews, abbreviations are used to describe

Table 1
Description of interview participants, including the abbreviation, number of interviewees per actor and general description of their input and output product. Between the brand owner and waste management company are the consumption & disposal stages.

Actors	Abbreviation	Number of interviewees	Input product	Output product
Polymer producer	POL PR	3	Naphtha, natural gas, additives, monomers, pyrolysis oil, stabilizers	Polymers, plastics (polymers + additives) pellets
Additive producers	ADD PR	3	Base and fine chemicals	Additives and/or functional materials (e.g., inks, adhesives, and barriers)
Converter	CON	4	Plastic pellets, additives, processing aids, functional materials	Packaging
Brand owner	BO	6	Packaging	Final packaged product
Waste management company	WMC	2	Plastic packaging waste	Sorted plastic packaging waste streams
Mechanical recyclers	MR	5	Sorted plastic packaging waste streams	Plastic pellets, washed flakes
Chemical recyclers	CR	3	Sorted plastic packaging waste streams	(Upgraded) pyrolysis oil, monomers
Original equipment manufacturers	OEM	2	–	–

interviewees.

The converter actor group includes intermediate packaging converters, packaging converters as well as product converters. With ongoing vertical integration, interviewees sometimes also provided their knowledge of other operations than their 'main' operations. In these instances, we included their answers into the actor role of the relevant operations. The interviewed polymer producers also have their own crackers, so their input is naphtha and/ or natural gas and they first make monomers before making polymers.

One of the interviewed mechanical recyclers does not recycle packaging but other (non-packaging) films. The interview is included in the analysis because it does have a valid contribution to the research on several aspects. We also included original equipment manufacturers, the actors who provide equipment for waste management companies and recyclers, because they have knowledge of quality and processes as well. While their perception on quality is not directly included in the results, their answers during interviews do confirm and build on what other actors mentioned.

The approximately one-hour interviews were held online and recorded. The questions in the interviews were specifically focused on their perceptions of quality (and differences/similarities between actors), influences on quality, improvements of quality, and collaboration in plastics packaging recycling. For this paper, the emphasis is on the answers to the questions on perceptions of quality. However, we also included discussions related to other questions asked that contribute to the aim of the research. The Supplementary Information provides an interview guide and more details on methodology.

3.3. Data processing & analysis

All interviews were machine transcribed in their original language. To ensure accuracy of transcripts, the transcribed documents were checked and corrected manually. The transcribed interviews were coded and analyzed in Atlas.ti and Excel with an inductive approach and using simultaneous coding (Saldana, 2017) (applying multiple codes to the same quote). We conducted a thematic analysis where we first analyzed the quality categories per actor, followed by the actor interactions.

Fig. 2 Visualization of the used nomenclature provides a visualization of the terms we use in this paper. One or several quality features can be assigned to a specific quality category (e.g. elastic modulus and stiffness are part of a category called 'mechanical properties'). In turn, a combination of quality categories creates the quality perception of a specific actor.

By identifying relevant codes with a co-occurrence analysis and subsequently categorizing these codes, in total we identified nine quality categories based on mentioned quality features. We purposefully excluded non-quality and non-product related requirements such as yield, and wastewater. For the actor interactions, we investigated the perceived differences and similarities described by the interviewees. Again, we used a co-occurrence analysis by selecting only one actor group at the time. Next, we visualized the similarities and categorized the differences into overarching themes.

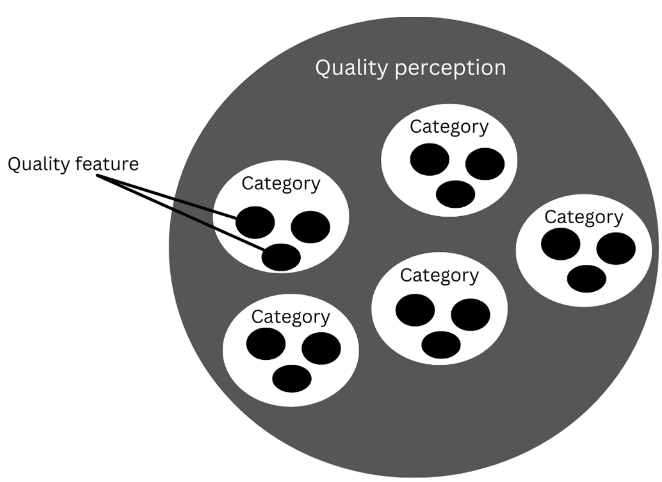

Fig. 2. Visualization of the used nomenclature with respect to quality perception.

4. Results and discussion

4.1. Quality categories

Interviewees described quality features for their input and output products. We aggregated these into the nine quality categories shown in Table 2, and linked these categories to existing literature which also use them. Table 2 shows these categories including a brief description and links to literature references that describe methods of quantification for these categories. The Supplementary Information provides a detailed overview of specific quality criteria per actor for their input and output product.

4.1.1. Quality categories in the system

Actors identified different quality categories as important. Table 3 provides an overview of the relevant categories described per actor. The categories actors perceive for their input are described under 'IN', and for their output under 'OUT'. A grey-colored cell means that the quality category is part of the quality perception of the actor. The Supporting Information provides more details on the example quality features which actors mentioned.

Fig. 3 provides a comprehensive view of the quality categories

Table 2
Overview of categorized quality categories, including a description and references where these categories are mentioned.

	Quality categories:	Description:	References
1	Circularity	Aspects such as recyclability, usage of recycled content, and reusability	(Cimpan et al., 2023; Santi et al., 2022; Stumpf et al., 2023)
2	Uniformity	Homogeneity of composition over streams/ feedstocks and time	(Antonopoulos et al., 2021; Brouwer et al., 2020; Kawai et al., 2022; Kleinhans et al., 2021; Vogt et al., 2021)
3	Purity	Degree of contamination allowed at an input or output (other than target product)	(Eriksen et al., 2018; Friedrich et al., 2020; Hahladakis and Iacovidou, 2019; Johansen et al., 2022; Kusenberg et al., 2022a)
4	Functionality	Performance of the final application	(Lindh et al., 2016; Mager et al., 2023; Vadenbo et al., 2017)
5	Processability	Material behavior during processing, such as viscosity or Melt Flow Index (MFI)	(Demets et al., 2021; Eriksen et al., 2019; Golkaram et al., 2022)
6	Mechanical properties	Mechanical properties of the material, such as tensile strength and E modulus	(Bashirgonbadi et al., 2022; Dahlbo et al., 2018; Tratzi et al., 2021)
7	Regulations & safety	Regulations or safety aspects. *E.g.,* food contact regulations, and substances of concern (SoC)	(Eriksen et al., 2018; Rung et al., 2023)
8	Physical properties	Physical properties of the material, such as density, melting point, odor, aesthetics and color	(Bashirgonbadi et al., 2022; Friedrich et al., 2020; Golkaram et al., 2022; Schulte et al., 2023)
9	Substitutability	Ability to replace a virgin-based material for a recycled material	(Demets et al., 2021; Eriksen et al., 2018)

Table 3
Identified quality categories per actor. Substitutability of POL PR-IN was identified as quality category if pyrolysis oil was the input, and not for the input fossil-based oil.

Actor	POL PR		ADD PR		CON		BO		WMC		MR		CR	
Quality category \ IN/OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT
Circularity			■	■		■	■	■						
Uniformity				■		■	■	■				■	■	
Purity	■	■	■	■	■	■	■		■	■	■	■	■	■
Functionality			■	■	■	■	■	■				■		
Processability				■	■	■	■					■		
Mechanical properties		■	■	■	■	■	■					■		
Regulations & safety		■	■	■	■	■	■	■				■		
Physical properties	■	■		■	■	■	■	■				■		■
Substitutability	■											■		■

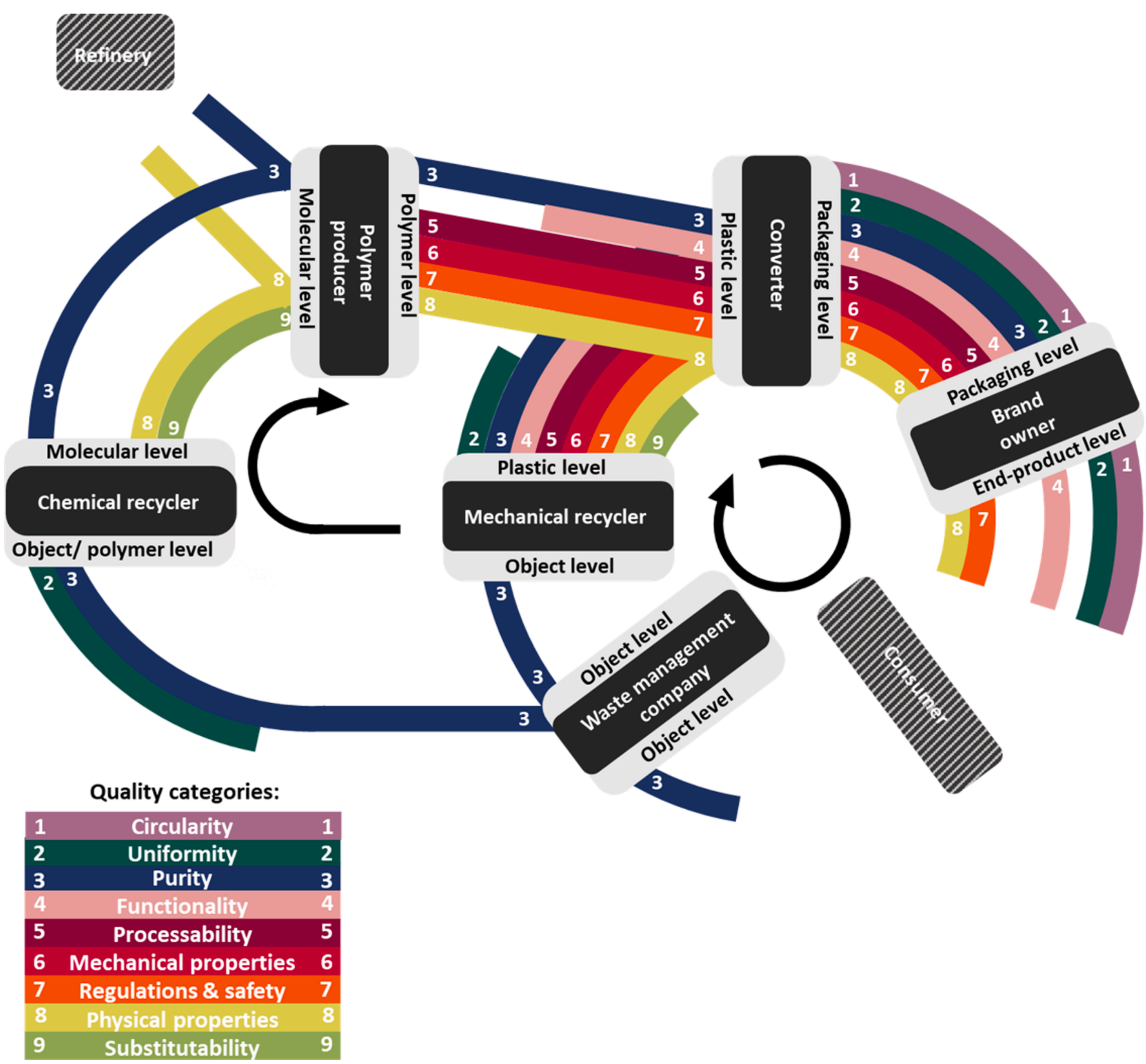

Fig. 3. System overview of quality categories including all actors. Each colored line represents a quality aspect. A full line between two actors shows alignment on the quality aspect. A half-empty line means that an actor did not mention aspects related to the quality category for their input or output product.

mentioned in the system. It combines the above-mentioned results from each actor with the material flow along the chain. A completely filled line between two actors shows that both subsequent actors focus on the same quality category and their perceptions match. A half-filled line (e.g., 'substitutability' between the mechanical recycler and converter) means that the category was mentioned only for an input or for an output. Additive producers are excluded from Fig. 3, since it was unclear at times if their output would go to a polymer producer or a converter.

4.1.2. Discussion on quality categories

All actors have quality features related to the purity category for their input and/or output product. However, there is a broad scope of 'contamination' (meaning substances other than the main polymer) allowed in products, which results in different interpretations from actors. Contamination can occur on all levels ranging from molecular to object level, and can be categorized into designed and created contamination (Hahladakis and Iacovidou, 2018). Designed contaminations are materials that were purposefully added to the target product (intentionally added substances), which become contaminants in the recycling stage (e.g., printing inks) and created contaminations are not purposefully added materials to a product, often called non-intentionally added substances (NIAS) (Horodytska et al., 2020; Kato and Conte-Junior, 2021).

The functionality category was not described by polymer producers while converters and brand owners did describe it. The reason for this difference could be that polymer producers look more directly at the mechanical and physical properties (material properties), which the converter and brand owner might translate into product properties (functionality). Moreover, converters can combine the properties of different polymers to create the right functionality for their plastic packaging. So, the output product of the polymer producer can be combined with other output products to acquire the desired end-product performance. Therefore, it might not make sense to focus explicitly on functionality of the output as polymer producer. Nonetheless, the inclusion of categories describing material properties (categories 5–8) do imply a 'fit for functionality'.

In comparison to the foundation literature on generic quality definitions (Garvin, 1984; Reeves and Bednar, 1994; Seawright and Young, 1996), actors in the plastics packaging material chain adhere to slightly different categories but the principles are similar. Garvin's (1984) quality dimensions, for example, can be linked to our quality categories. Performance, reliability, conformance, and durability are related to the functionality quality category we describe. The dimension 'features' is related to the properties categories, and 'aesthetics' is specifically related to the physical properties category. In hindsight Garvin's perceived quality dimension does not fit in any of our categories. The reason for this could be that we focus on actors in the material chain that have a set of measurable requirements, so it is not dependent on perception. However, one could argue that since perceived quality is related to aesthetics as well, it links to the quality category of 'physical properties'. We find that Garvin's serviceability dimension, the ability to repair, is related to recyclability which is covered by the quality category of 'circularity'.

While circularity features such as, using recycled content and design for recycling, were described by some actors (additive producer, converter, brand owner), many did not describe circularity features. Actors with circularity as a quality category are on the design for recycling side, where the focus is on improving the recyclability of products. The actors not describing circularity as a quality aspect play a direct role in recycling (or are making a shift to include recycling processes in their business models), which could mean that circularity is unspoken but implied. Additionally, we did not include circularity efforts described by participants that were not linked to the quality perception of their input and output product (*e.g.*, using renewable energy and reducing CO_2 emissions in a process).

4.1.2.1. Multifaceted categories. There is no single perception of quality and the quality categories described are interconnected. The functionality quality category is related to the performance of the product, which comes from the properties of the product. Moreover, some of the brand owner's input and output quality features of the packaging are similar because they often purchase the packaging from a converter (input product) and fill it with their product (output product).

Depending on the actor, the meaning of certain quality categories differs, thereby amplifying its complexity. For example, all actors described quality features related to purity, but these features differed per actor. Waste management companies consider the purity of their output on an object level, mechanical recyclers on a plastic level (polymers including additives), and chemical recyclers on a molecular level. Additionally, the quality features related to physical properties can be separated into subjective (e.g. appearance and aesthetics) and objective properties (e.g. boiling point, color, shape).

The substitutability category was perceived on different levels when comparing the output quality perception of mechanical and chemical recyclers. It is a combination of other quality categories and bound to a specific application. Mechanical recyclers perceive substitutability as the ability to use their recyclate as a replacement for virgin plastics for targeted applications, which is similar to descriptions in current literature (Demets et al., 2021; Golkaram et al., 2022; Huysveld et al., 2022; Rigamonti et al., 2020). Chemical recyclers see substitutability as a replacement for naphtha, which could be applied for any application. However, in terms of quantity it is not a complete substitution according to interviewees since pyrolysis oil is added to fossil-based naphtha to make new polymers.

Converters did not describe substitutability as a quality category of their input product, which could be because they already expect their input to be of the right quality (based on e.g. mechanical properties and processability) for their specific applications. Thus, not necessarily perceiving it as substitutability, but perceiving it as compliant with required specifications. Ultimately, the substitutability category is the same, but the perception and description of substitutability is different for converters and recyclers.

Quality is very dependent on the application, and we advocate that it should not be generalized into levels based on a single quality aspect. Some actors described the regulations & safety category as most important. This aligns with several studies that define quality of a product based on regulations & safety aspects (Eriksen et al., 2019, 2018; Faraca and Astrup, 2019). However, we challenge the belief that quality should be separated into high and low-quality categories solely based on safety requirements because several (non-food) applications focus their requirements more on mechanical and physical properties. Thus, we argue that quality should be classified based on the substitutability of recyclate into the desired application. This functional substitutability should be measured by the relevant quality requirements for the specific application, as several studies already suggested by offering substitutability tools (Demets et al., 2021; Golkaram et al., 2024, 2022).

In conclusion, we identified nine quality categories that actors adhere to. The combination of the interconnected quality categories and different meanings for each actor results in a web of quality perceptions. Understanding this complexity is important to have better alignment in terms of processes in the material chain. This could result in an improved recycling system (Pajunen et al., 2016). The identified quality categories have a lot of overlap with generic quality definitions (Garvin, 1984). However, the circularity category is new in comparison to these older quality studies, but is also not directly seen as quality category by a large part of the actors. Furthermore, substitutability, whether described or not by actors, does come down to the same concept. While there seems to be a lot of overlap with existing literature on generic quality categories and some quality concepts are similar, this study provides a holistic overview of the quality perceptions of actors in the material chain. Lastly, we believe that actors and literature should not define quality as 'high' or 'low' based on one quality aspect, since it is highly application dependent. One recyclate might have a high quality for one possible application, but the same recyclate could have a low quality for another application (Demets et al., 2021; Golkaram et al., 2022).

4.2. Actor interactions

In this section we discuss results on the perceived actor interactions and whether they are aligned or mismatched. We discuss alignments in quality perceptions, then we investigate differences in quality perceptions.

4.2.1. Alignments in quality perceptions

Fig. 3 showed that there are many similar quality categories between subsequent actors, implying they have a similar quality perception. However, when we asked actors directly if they notice any similarities between their quality perception and quality perceptions of other actors in the chain, actors did not describe many similarity connections between their subsequent partners in the chain. Fig. 4 provides an overview of the perceived similarities in quality categories. The light-colored connections show the actors with matching quality categories based on Fig. 3 (but which were not described as having a similar quality perception by both actors), and dark-colored connections show a directly described similarity in quality perception from both actors. Additionally, the arrows indicate which actors described a similarity in quality perception towards another actor. As can be seen in the Figure, only the polymer producer and converter both described similarities in quality perceptions.

While the section on quality categories shows many matching categories between actors, results from interviews show that actors barely perceive themselves to have similar quality perceptions with their previous or subsequent actors. As Fig. 4 shows, there are mostly one-sided perceptions on similarities. We believe this discrepancy between identified categories and perceived similarities can have various reasons. Actors could be either unaware of the similarities or are aware of the similarities but did not acknowledge them because they find them too obvious. Another reason could be that even though the categories are the same, they might have different meanings to actors, or they are perceived on different levels and are therefore not mentioned as having a similar perception. Regardless of the reason, this result does show that more understanding of quality perceptions between actors is required.

4.2.2. The influence of the consumption and End-of-Life stage

As Fig. 3 illustrates, the brand owner focuses on several quality categories for their output product, whereas after consumption, the waste management company only focuses on one quality category for their input. Unavoidably, at the post-consumer stage, products that initially adhered to many quality categories (and their connected criteria), are collected into one complex waste pile, resulting in a transition from multiple quality categories to just one. Subsequently, during the recycling process, the actors undertake efforts to expand the material's quality again, to several quality categories for the output product.

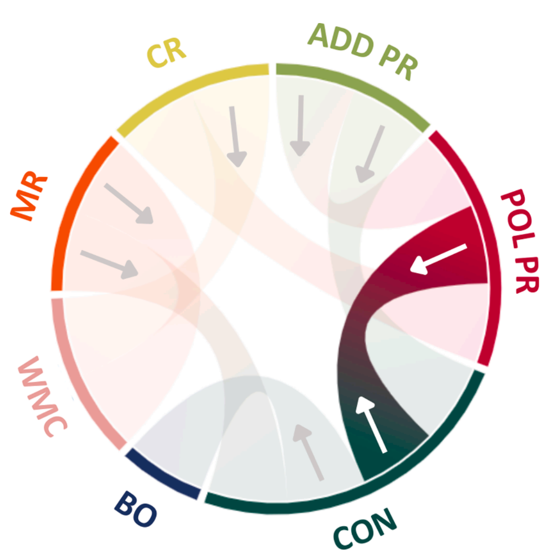

Fig. 4. Perceived similarities in quality perception. The arrows represent actors that mentioned to have a similar quality perception with another actor. The dark-colored connection means that both actors perceived each other to have a similar quality perception (arrows go both ways).

4.2.3. Differences in quality perceptions

Next to similarities, interviewees also explicitly described differences in quality perceptions between actors. We identified five themes of differing quality perceptions. In the following sections, we elaborate on these themes. The presentation order of these themes does not suggest any hierarchy or sequence.

4.2.3.1. Stacking of quality requirements. As shown in Fig. 5, interviewees from polymer producers, converters, and brand owners described a stacking of quality requirements. The type of quality categories barely changes, but the strictness and details of categories do, which sometimes leads to frustration with the actors. A brand owner described that they are much stricter on safety requirements than a converter and the converter is again perceived to be stricter on safety than a resin producer. Another example which converters described is odor. It was mentioned by a converter that mechanical recyclers and sometimes polymer producers claim that their resin is odorless, whereas the converter perceives this is often not the case.

Moreover, brand owners engage in a more thorough examination of the performance of the final product, while converters translate this performance into properties for the packaging, and the polymer producers translate these again into properties of the polymer. Quality is related to what is accepted by the market and in the end, actors communicate together to try to align on the final quality requirements.

Because actors define their input and output products on different levels, it is understandable that they adhere to slightly different requirements. Moreover, the requirements typically originate with the brand owner and are then communicated upwards to the previous suppliers in the chain (Rundh, 2013). Brand owners might also need to comply with safety requirements for example for food packaging (EC, 2004). These requirements would also be translated to the converters and the polymer producers supplying the input product. This links to the concept of total functional value from Vulsteke et al. (2024) which consists out of material, product, and component functional value.

4.2.3.2. Recyclate from original mechanical recyclers vs new mechanical recyclers. More and more polymer producers are vertically integrating into the chain by participating in (chemical and/or) mechanical recycling (Gao et al., 2023; LyondellBasell, n.d.; Sabic, n.d.). Consequently, a difference arises between mechanical recyclers of which recycling is historically their main operation (from hereon named 'original mechanical recyclers') and polymer producers who transitioned into

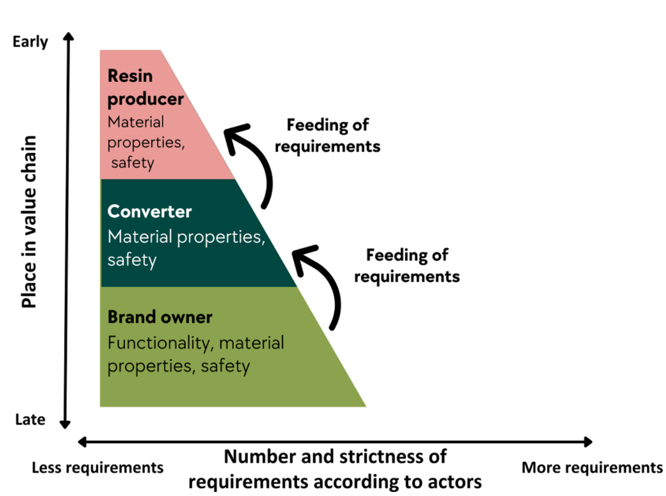

Fig. 5. Simplified illustration of stacking concept. Quality requirements are fed to actors earlier in the chain.

mechanical recycling (from hereon named 'new mechanical recyclers'). Brand owner and converter interviewees described that – from their polymer knowledge – new mechanical recyclers focus more on quality, while original mechanical recyclers focus more on volumes (in combination with also having the highest possible quality application). Especially in plastic film recycling, the recyclate from new mechanical recyclers is perceived as a higher quality grade compared to pellets from original mechanical recyclers. As shown in Table 3, the alignment on quality requirements is not perfect between the input of the brand owner and output of the mechanical recycler. Therefore, interviewees described collaboration as necessary to meet the right quality criteria. It was also mentioned that a (original) mechanical recycler does not always provide a full analysis of all quality specifications of their output.

Noteworthily, this presumed difference in quality-quantity focus is in stark contrast with the perception of original mechanical recyclers themselves. As shown in the quality perceptions section of mechanical recyclers (all interviewed mechanical recyclers were original mechanical recyclers), the interviewed participants emphasized that they (aim to) produce recyclate with similar properties to virgin pellets.

4.2.3.3. Bale specifications for waste management companies vs mechanical recyclers. Waste management companies described that they must sort according to quality specifications imposed by a PRO, which is based on the amount of contamination on the object level often from Der Grüne Punkt (DSD) or similar specifications. For example, the DSD specification for PP (DSD-324) (Der Grüne Punkt, n.d.) describes that the sorted stream of PP should have at least 94 % of the PP target material on the object level, based on the main component. This means that for example, the labels and lids attached to PP packaging are included in this 94 % even though they consist of different materials. While the waste management companies argue that they sort according to standards, several mechanical recyclers mentioned that their input material often includes a higher level of contamination than what is allowed according to the imposed standards. One interviewee described that there is a difference in terms of purity of inputs from waste companies with a direct partnership (who deliver higher purity) and waste brokers (who deliver lower purity).

Moreover, the mechanical recyclers described that they still accept the material as input even though it has more contamination than the specifications allow because sometimes waste management companies are not able to sort according to specifications due to limiting technologies (also described to be country-dependent). Additionally, they mentioned that there is sometimes scarcity in the market for some sorted product streams, therefore they then have no other choice than to accept the lower purity input sorted product streams. However, they also argue that for lower purity sorted product streams they sometimes ask for financial compensation (so-called gate fee). Next to DSD specifications, some mechanical recyclers also have different wishes in terms of maximum contamination allowed of specific materials.

The discrepancy in bale quality perception might be explained by a lack of incentives for waste management companies to sort out more non-target products than the maximum amount required (e.g., instead of sorting out 6 % non-target products, sort out 2 %). With Extended Producer Responsibility (EPR) in place (EC, 2008), the PRO sets these requirements based on for example DSD specifications. If they sort out more non-target plastic objects, they only decrease the quantity of their target sorted product stream, which in return reduces the turnover of their sorted stream. Moreover, it creates more residual waste, which increases the costs for the waste management company or the PRO.

4.2.3.4. Input specifications for chemical vs mechanical recycling. A mechanical recycler described that for compositional requirements, more is allowed in chemical recycling, however a chemical recycler stated the complete opposite. They provided the example that the input for pyrolysis should not include more than a certain percentage of halogens, since these are highly corrosive materials capable of damaging the equipment and that in terms of substances of concern, such as plasticizers and flame retardants, requirements on chemical recycling are very strict in comparison to mechanical recycling. In terms of output quality perspectives, chemical and mechanical recyclers look at their output on very different levels. While mechanical recyclers consider the material properties of the pellets, chemical recyclers consider the pyrolysis oil on a molecular level.

Currently, chemical recycling requirements are perceived to be stricter than mechanical recycling requirements in terms of contamination restraints. However, if mechanical recyclers desire to have their recyclate applied in for example food-contact applications, then they would also have to comply with the relevant regulations (De Tandt et al., 2021; EC, 2022). With the ongoing drive to increase circularity, stricter regulations might come into play as well for mechanical recycling. The proposal for Packaging and Packaging Waste Regulation includes a minimum percentage of recycled content of plastics in packaging applications (European Commission, 2022). This could require actors in the chain to be stricter on certain quality categories to reach technical feasibility of applying recycled content in new packaging. Especially for polyolefins this might become a challenge because of legislation (Cecon et al., 2021).

4.2.3.5. Internal misalignment at brand owners. Most brand owners mentioned that they have internal differences in quality perceptions. This is caused by the different drivers in departments. While marketing is, for example, focused on aesthetics, the packaging department focuses more on the technical properties and sustainability and procurement on the costs of materials. This misalignment between departments was described to sometimes cause friction in decision-making processes.

Depending on the department, the quality perception might differ. Van Hoek and Mitchell (2006) also describe this phenomenon of misalignment in an organization, which they state could limit the overall supply chain efforts. They find that cross-training and improving interpersonal and communication skills could help overcome these issues.

5. Conclusion & recommendations

The main goal of this study was to acquire a better understanding of the quality perceptions of actors in the material chain for plastic packaging, which was previously undocumented. In terms of quality perceptions, we identified nine quality categories, based on quality features described by actors: purity, uniformity, mechanical properties, physical properties, processability, functionality, regulations/ safety, substitutability, and circularity. Each actor in the material chain described quality features related to one or more of these categories. These categories can be related to the principles of generic quality definitions described in foundational literature (Garvin, 1984; Reeves and Bednar, 1994; Seawright and Young, 1996), with the addition of circularity. Results show that subsequent actors have mostly matching quality categories for their output and input products. Only a few quality categories do not match between actors. Substitutability is a quality category only mentioned by actors active in recycling. The quality category 'purity' was described at least once by all actors; however, the meaning of purity depends on the actor and on the level that they observe quality. The interrelated quality characteristics and different meanings for each actor create a web of quality perceptions. This study demonstrates that with these different existing perceptions on quality from actors, using the term 'high quality' on itself is insufficient. Instead, 'high quality' requires to be made more specific and ideally measurable. Understanding this complexity is critical to improve material chain process alignment.

Regarding actor interactions, even though the quality categories of subsequent actors are similar, they rarely acknowledged this similar perception in quality. Furthermore, there were also several key differences in quality perceptions which we identified in five themes: stacking of quality requirements, recyclate from mechanical recyclers vs polymer producers, bale specifications of waste management companies and mechanical recyclers, input specifications for chemical vs mechanical recycling, and internal misalignment at brand owners. These themes can be seen as challenges that might need to be overcome to shift to a circular economy for plastics.

Overall, this research shows that quality perceptions differ, and actors rarely have a good understanding of each other. In order to shift to a circular economy (for plastics) collaboration between actors is important (Foschi and Bonoli, 2019; Salmenperä et al., 2021; Sudusinghe and Seuring, 2022). In turn, to collaborate, being aligned or at least having an understanding of actors in the chain is essential (Brown et al., 2021; Kujala et al., 2023). By providing an overview of the quality perceptions and interactions in the material chain, this research contributes to this increased understanding on quality perceptions of actors.

5.1. Shortcomings & outlook

It is not feasible to standardize all nine quality categories for each actor across the entire material chain. However, actors should at least be aware of the differences in quality perceptions. Moreover, quality perceptions at least from the output of a previous actor to the input of the subsequent actor, should be aligned in categories and its measurement, which is currently not always the case (e.g. as Section 4.2.3.3 shows on the bale specifications from a WMC and MR). The section on actor interactions provides a general idea of differences in quality perceptions. We believe there is more research needed to uncover the underlying reasons for the quality differences and potential solutions to overcome these differences. More interviews with organizations from the same actor groups are recommended to acquire a complete overview of all the quality interactions with illustrative examples. However, we do believe that this exploratory research provides the basis of quality perceptions in the plastics packaging material chain. The aim of this research was to look at the physical material chain, and its actors. Therefore, we excluded actors that do not have a converting role. These actors, such as PROs and governmental organizations, will be included in our future research on the topic since they can have a major influence on the system with their quality perception. Moreover, while the included waste management companies are involved in both collection and sorting, the main topic during interviews was at sorting. Future research should also include more on the collection perspective.

The topic of measuring quality was out of scope for this research. This study's quality categories per actor provide a nice foundation for future research to go in-depth on how each identified quality category should be measured.

The plastics system needs to change in order to shift to a circular economy for plastics. The overview of quality categories per actor that our results visualize could serve as the foundation for future research on improvements. Having a general understanding of the quality perceptions of actors is essential in understanding the improvements they perceive necessary in terms of quality to shift to a circular economy for plastics. Further research should explore the improvements that actors perceive as necessary in the chain, and the actors that should take responsibility for these actions.

CRediT authorship contribution statement

Merel Molenbuur: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Marcel C.P. van Eijk:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Jan Harm Urbanus:** Writing – review & editing, Conceptualization. **Henk Diepenmaat:** Writing – review & editing. **Kim Ragaert:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

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Data availability

The authors do not have permission to share data.

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